# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**DIRTY BOMBS: THE TECHNICAL ASPECTS OF RADIOLOGICAL DISPERSION DEVICES**

by

Benjamin Felix Visger

June 2004

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**DIRTY BOMBS: THE TECHNICAL ASPECTS OF RADIOLOGICAL DISPERSION DEVICES**

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Submitted in partial fulfillment of the
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# ABSTRACT

Considering the ever-rising threat of terrorist attack and disruption of the economy and of daily activity, the potential strength of a radiological dispersion device must be evaluated. A “dirty bomb” is a weapon in the terrorist arsenal that is highly effective in creating chaos, panic and disruption. All of the immediate deaths caused by a “dirty bomb” are due to blast effects, however the public association with radiation and nuclear devices is one of fear and hyperbole. The individuals and agencies that respond to this type of event will have the greatest impact on the general public. By looking at case studies and potential scenarios or exercises the first responder can appreciate the nature of radiation as well as its impact on response. The goal of this paper is to provide first responders with basic information on nuclear physics and expose relevant issues in responding to a radiological dispersion device. An understandable link between nuclear physics and radiation response does exist.

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I would like to acknowledge the first responder community for the countless hours dedicated to protecting the public and for seeking better ways of combating terrorism. I had the opportunity to meet and hear from as well as learn about the first responder community during the monthly Bay Area Terrorism Working Group (BATWING) meetings. Those meetings provided me with a better understanding of how this important community operates. I would also like to thank Professor Maruyama for his direction and perspective while working on this project, and recognize Russell Coile for his contributions derived from years of experience in emergency response. Finally, I would like to thank Maria Carolina Roa for her constant support and encouragement during the course of this project.

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# I. INTRODUCTION

## A. GENERAL DISCUSSION

The "battlefield" of the twenty-first century is no longer confined to locations where massed armies or navies confront each other. One of the most unpleasant facts of the world today is the prevalence of unconventional warfare where civilians and civil infrastructure are targeted. In many instances, these are manifest as terrorist acts. Because of media coverage and the associated publicity, the most spectacular criminal terrorist acts are committed, not necessarily to induce the greatest numbers of casualties, but to have the greatest psychological impact upon the general public. “Dirty Bombs” or Radiological Dispersal Devices (RDD) may be used as a means to these ends because in the eye of the public they are associated with nuclear weapons, fall out and with cancer susceptibility. Historical cases have also shown that the general public typically responds fearfully and ignorantly to incidents that involve the use of nuclear or radioactive materials. This report will provide scientific understanding of radioactivity and the material used for making dirty bombs, as well as consideration of possible scenarios and some historic examples, to provide a realistic assessment of RDD’s and their effects.

In most cases, a dirty bomb combines a conventional explosive, such as dynamite, with radioactive materials. The conventional explosive is constructed in such a way as to disperse radioactive material in the surrounding environment. (*This report does not deal with specific technical aspects of bomb design or fabrication. It assumes a bomb has been built that incorporates radioactive material.*) Ideally, the radioactive material is in a powdered form so that it will be blown around by the expanding gasses from the explosion and eventually be inhaled by people. Contamination is not only damaging when inhaled by people, it poses an external hazard to individuals as well. Radioactive dust can deposit on buildings and other structures to promote further economic damage and stigma. While radiation can be dangerous and even life threatening, immediate lethality is almost always due to the conventional explosive. Most likely, the amount of radiation is insufficient to kill people or even cause severe illness. In most cases, the primary concern is to treat life-threatening injuries first and then deal with factors associated with radioactivity.

Following a radiological dispersal device event, the most prudent action is to move away from the immediate area and seek shelter inside in order to reduce exposure to radioactive airborne dust. Typically, an explosive event lends itself well to this type of action because people instinctively move away from an area that has experienced an explosion. In the case of an RDD attack the first responder can be grateful for this type of instinctive action, because radioactivity is odorless, tasteless, and cannot be seen by a human eye. An explosion itself will not indicate a dirty bomb, as fundamentally there is nothing different between a wholly conventional explosive and that of a dirty bomb. However, if a radiological attack is suspected, removing potentially contaminated clothing and showering in addition to remaining inside will help to reduce further contamination. Saving contaminated clothing in a sealed plastic bag will allow for later testing and a determination of exposure.

A dirty bomb should be considered a strategic weapon, not a tactical one. The perceived threats of a radiation and anything nuclear, combined with real threats make this weapon one of mass disruption and of fear rather than of mass destruction. A radiological dispersion device is most disruptive when placed in an area that effects large numbers of people such as a business district, subway station, or entertainment district. By striking one of these targets not only would many people be directly affected, but also the lasting consequences mean decreased traffic and productivity in the area.

In the event of a dirty bomb attack, the immediate danger is not radioactivity. With this realization about priorities of concern, it must be recognized that dirty bombs could contaminate relatively large areas, causing panic, creating fear and requiring costly and difficult cleanup efforts. Truly the relatively small amount of radiation released by a radiological dispersion device may be insignificant when compared to other more far-reaching consequences. An entire city central could be contaminated beyond acceptable levels prompting very large and specialized decontamination efforts. Some structures could be rendered permanently contaminated and have to be quarantined or destroyed and carried away to a special storage site. Even if an area is completely decontaminated, the economic loss to the area or even the entire city could be very consequential. People tend to be afraid of radioactivity, business would loose patrons and they may never return. Simple education about the general physics concerning the realities and details of dirty bombs and their associated radioactivity can help considerably in deciding how to respond sensibly to a radiological dispersal device event.

## B. HISTORIC PERSPECTIVE

During the Cold War the term ***dirty bomb*** was coined to describe a nuclear weapon exploded close to the earth's surface resulting in radioactive products mixing with surface materials and spreading radioactive fallout far and wide. "Cleaner" bombs were made possible by higher altitude detonation in which the fireball did not come in contact with the surface. Truly dirty bombs have been envisioned wherein relatively short lived cobalt-60 or other radioactive isotopes could be incorporated into the bomb design to maximize residual radioactivity in the target area. These "dirty bombs" result in nuclear explosions and are fundamentally different from the dirty bombs of concern in the context of a terrorist attack.

In the context of this study, dirty bombs or radiological dispersion devices (RDD) are conventional explosives such as dynamite packaged with radioactive material that scatters when the bomb detonates. A dirty bomb kills or injures through the initial blast of the conventional explosive, while airborne radiation and contamination may provide a source for longer term physical and physiological effects. Such bombs could be miniature devices or as large as a truck bomb. Other types of crude devices may also be considered RDD's, from a contaminated piece of material that is passed around to a contaminated bag or container left in a public space, even a crop duster loaded with radioactive material. Terrorists have many options when it comes to distributing radioactive materials, but a fantastic explosion and the slightest mention of radioactive contamination generate real fear.

Cursory perusal of magazine headlines show very little interest in "dirty bombs" until about March 2002. Key to bringing the topic to the interest of the American public was the testimony of Dr. Henry Kelly, President of the Federation of American Scientists, before the Senate Committee on Foreign Relations.[i] In his testimony three scenarios of radiological attacks are presented with the conclusion that they constitute a credible threat; attacks could contaminate large urban areas; and large areas may need to be evacuated even if radiation casualties are low. A further analysis of the scenarios presented in his testimony is discussed later. On May 8, 2002, Jose Padilla, aka Abdullah al-Muhajir, a 31-year old American, was arrested in Chicago, accused of being involved in a plot to place a radioactive dirty bomb in the Washington metro system.[ii] After Kelly's testimony and Padilla's arrest, the media became filled with concerns about dirty bombs.

The perception of the danger resulting from the effects of a dirty bomb can be traced to a general public fear of many things nuclear. Besides the atomic bomb used in World War II, our experiences with the Three Mile Island reactor accident in Pennsylvania, the Chernobyl reactor accident in the Ukraine and the death of four people, including a six-year-old girl, from radiation sickness in Goiana, Brazil in September 1987 have heightened public awareness of the possibility of radiological effects. Despite the relative heightened awareness, the media tends to sensationalize these incidents blurring the actual facts and real concerns.

The first-ever attempt at radiological terror is thought to have occurred in Ismailovsky Park in Moscow, Russia in November 1995.[iii] A group of Chechen rebels contacted a Russian television station and boasted about their ability to construct a radioactive bomb. They alerted the press and a 13.5 kg. (30 lb) cache of cesium filled radiological material was found partly buried, though much of that 13.5 kg source was likely shielding material. Chechen separatists gave the location of three other sites where radiological materials had been placed and stated that these sites also held conventional explosives. These were not found. The individuals who planted the cesium-137 in Ismailovsky Park have not been identified nor has the original source of the material.

In December 1998, the head of the Russian backed Chechen Security Service, Ibragim Khultygov, appeared on Chechen TV and announced that a container "full of radioactive substance and a mine attached to it" was found some 15 km east of Grozny, the Chechen capital. The mine was deactivated, without much information given, but Chechen rebel involvement was suspected.[iv] The existence of a rebel explosive workshop near the suburb of Argun, headed by warlord Shamil Basayev, gave credence to the suspicion.

Outside of these two instances, there have been other reports of seizures of dirty bomb material in the former Soviet republic of Georgia, and elsewhere.[v,vi] Recently, one of these reports dealt with the seizure of metal containers, holding cesium-137 and strontium-90, during a raid near the country's capital of Tbilisi, on May 31, 2003. It is suspected that containers were to be transported out of the country to Turkey where they could be resold. The final market for the materials may have been Chechnya. Along with the containers, police also discovered a glass capsule containing Yprite, or mustard gas. Mustard gas incorporated into a dirty bomb, combined with explosives and radioactive materials could cause an increasingly dangerous and frightening affect.

It is reported that the seized containers held three curies of cesium and 12 microcuries of strontium. Though the amounts may sound large, the physical quantities involved were of the order of 34 milligrams of cesium and 1.7 milligrams of strontium. In contrast, the largest known seizure of weapons-grade uranium from the former Soviet Union was also in Georgia. Police arrested three men in 2001 attempting to sell nearly four pounds of uranium-235. Again, this may seem like a large amount of material, however this constitutes 35 millicuries of activity and less than 4% of the material necessary to create a Hiroshima type nuclear bomb. Even in an advanced government facility, this is still only about 12% of the material needed for a sophisticated modern nuclear weapon.

## C. POSSIBLE SCENARIOS

On March 6, 2002, Dr. Henry Kelly, President of the Federation of American Scientists (FAS) presented testimony before the Senate Committee on Foreign Relations.[vii] His testimony increased the level of public awareness and alerted people of the real possibility of a radiological attack. In his testimony, he presented three RDD scenarios: dispersal of cesium from a medical gauge, of a cobalt source from a food irradiation plant and of americium from an oil well surveying instrument. Comparison was made to Chernobyl and to EPA safety guidelines. Analyzing these scenarios from a separate viewpoint finds that the general conclusion is one of weapons of mass disruption and mass misinformation, rather than mass destruction.

Knowledge of shielding requirements for the handlers, of newer studies of the Chernobyl aftermath and the recognition that NRC safety guidelines are based upon almost assured negation of cancer possibility for population in a lifetime, present a more realistic view of practical risk assessment. Regulations attempt to provide a strict legal limit on exposure, but the reality is that each individual responds differently to a given exposure. Legal limits provide a working basis for evaluations and attempt to keep people safe. The Nuclear Regulatory Commission (NRC) dictates that the occupational limit, assumed to be the limit for safe exposure in the event of an RDD, is 5 rems per year (0.05 Sv per year).[viii] Further discussion of biological affects, exposure, and radiation units are contained later in this report. The important thing to realize is that the actual results of exposure combined with the legal limits need to be considered for practical risk assessment.

The biggest challenge faced by the isotopes examined by Dr. Kelly, americium-241, cesium-137 and cobalt-60, lies in the relatively long half-life, 432, 30 and 5.3 years respectively. While people can evacuate a contaminated area and can even be treated for contamination, contaminated soil and structures may be impossible to clean and remain radioactive for hundreds of years.

## D. GENERAL CONCLUSIONS

Although radiological dispersion devices constitute a threat to which the general public must be aware, for the first responder the general consideration should be reaction to the conventional explosive effects. There is always a statistical possibility of incurring damage by radiation effects, but they pale in comparison to the immediate danger of injury and death from conventional effects. Recent history has shown the increasing interest of individuals and groups in obtaining radiological material for the production of RDD's. The existence of unsecured or easily accessible radiological material has prompted terrorists to seek these materials because of the fear they can impose upon the general public. However, as the interest in radiological material increases, more and more governments seek to control and account for radioactive sources. Determined individuals will always be able to obtain prohibited material, however the consequences must be determined by looking at the problem from many perspectives. Analysis of potential RDD scenarios shows that dirty bombs are likely to be more effective as a tool of fear and chaos rather than as a weapon for killing many people.

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# II. RADIATION

## A. LANGUAGE

Any discussion of radioactivity and radiation must contain definitions of quantities and units. Understanding the relative size of a millirem (mrem) or Curie (Ci) is necessary, as is understanding that the two terms describe different physical occurrences. Differentiation between activity, exposure, dose, dose rate, and effective dose, among others, must be made. Differentiation between statutory guidelines and physical cause and effect must be made. Traditional units, still commonly used in the United States, including (rem) and (rad) are defined in SI units as Sievert (Sv) and Gray (Gy) respectively. In radiation physics involving human beings, numbers with one or two significant figures mean more to the first responder than the precision of many significant figures. Despite a meter's capability of displaying five significant figures, the first responder will find it unnecessary to report all digits. Precision numbers belong in the laboratory and in technical reports, not in the operational world of the first responder.

## B. RADIOACTIVITY

***Radioactivity*** is the term used to describe the process in which an unstable nucleus releases excess energy. Atoms, or more precisely, isotopes of atoms exist that have too few or too many neutrons to be stable. An unstable nucleus tends to fall apart or decay, hence the term radioactive decay. There are a number of types of particles or photons in which a nucleus can release to diffuse its excess energy. These particles and how they decay are discussed later in the paper. Many times, an unstable nucleus decays into another unstable nucleus thereby creating what is known as a decay chain. Natural uranium, for example, goes through a 14-step decay chain in order to reach stable lead.

## C. ACTIVITY

The activity[1] of a radioisotope source is defined as its rate of decay. The historical (English) unit of activity is the curie[2] (Ci), defined as exactly $3.7 \times 10^{10}$ disintegrations per second. Originally, the curie was an estimate of the activity of one gram of pure radium-226 ($^{226}Ra$). A curie represents a relatively large source; more appropriate for typical laboratory work are the submultiples, the millicurie (mCi = 1/1000 of a Ci) and the microcurie ($\mu Ci = 10^{-6}$ Ci). Since 1975, the becquerel[3] (Bq) is defined as one disintegration per second. Therefore, a curie is $3.7 \times 10^{10}$ Bq.

It must be emphasized that activity measures the source disintegration rate and is not synonymous with the energy released by that activity. Determining whether or not a source is "dangerous" depends upon the particular radioisotope being considered.

**A useful concept is the *specific activity*, which is defined as the activity per unit mass of the radioisotope sample.**[4]

Take for example, 10 kg of weapons grade uranium, U-235 versus 1 g of strontium-90, a radioactive isotope used in former Soviet generators, and see which one

---

[1] The fundamental law of radioactive decay is: The activity, $dN/dt = -\lambda N$, where N is the number or radioactive nuclei and $\lambda$ is defined as the decay constant. $\lambda$is $1/\tau$, where t is the mean life, related to the half-life, $t_{1/2}$ by $\tau$ =, $t_{1/2}$ / ln 2. Consequently, the activity is proportional to the amount of radioactive material and is greater for those radionuclides with short half-lives. The half-life is defined as the time in which a sample of radioactive nuclei will decay to half its original amount.

[2] The Ci is named in honor of Marie Curie, nee Maria Sklodowska, (1859 – 1906), who won two Nobel prizes, one in Physics and the other in Chemistry. Her 1911 Nobel Chemistry prize was awarded for her discovery and isolation of radium. Marie Curie's daughter Irene married Frederic Joliet and the two jointly won the Chemistry Nobel prize in 1935. Marie's younger daughter, Eve, married the American Henry R. Labouisse. They were active in UNICEF when he accepted the 1965 Nobel Peace Prize on behalf of the United Nations Children's Fund.

[3] The Bq is named in honor of Antoine Henri Becquerel (1852 – 1908) who was awarded half the Nobel Prize in Physics in 1903 for is discovery of natural radioactivity I 1896. The other half of the Nobel Prize was shared with husband and wife team Pierre and Marie Curie for their study of Becquerel radiation.

[4] If a "pure" sample is obtained that is of only one nuclear species the specific activity can be calculated from: $SpecificActivity = {}^{Activity}\!/_{Mass} = {}^{\lambda N}\!/_{NM/Av} = {}^{\lambda Av}\!/_{M}$

| Symbol | Name | Description |
|---|---|---|
| $\lambda$ | Radioisotope Decay Constant | ln2/half-life |
| N | Number of Nuclei | |
| M | Molecular Weight of Sample | |
| $A_v$ | Avogadro's Number | $6.02 \times 10^{23}$ nuclei/mole |

is more dangerous on a strictly a radioactive basis. The specific activity of U-235 is $1.922 \times 10^{-6}$ Ci/g, thus 10 kg will have an activity of 19.2 mCi (milli-Curies)

$$(10kg) * (1000\ g/kg) * (1.922 \times 10^{-6}\ Ci/g) = 19.2\ mCi$$

The specific activity of Sr-90 is 139.4 Ci/g, thus 1 g will have an activity of 139.4 Ci

$$(1g) * (1000\ g/kg) * (139.4\ Ci/g) = 139.4\ Ci$$

Despite the fact that we have 10,000 times as much uranium as strontium, the strontium is nearly 10,000 times as radioactive as the uranium. Specific activity gives us an immediate sense of the relative radioactivity without going through this calculation every time. You can see why a very small sample of Sr-90 would be more dangerous than a large amount of uranium in a radiological dispersion device. Sr-90 is not used to make nuclear weapons, as U-235 is, however a radiological dispersion device is much simpler to produce than a nuclear weapon. Specific activity is also important because you cannot estimate the strength of a source based solely on its physical size.

## D. TYPES OF RADIATION

Radiation is a term used to describe many different types of energy, which is shuttled around the universe all the time. Radiation is as common as visible light or ultraviolet and infrared light. AM and FM radio waves, constantly bouncing around, are also a specific type of radiation. The radiation that we are concerned with is called ***ionizing radiation***, which carries much more energy than the other types of radiation mentioned. The purpose of a radiological dispersion device is to spread contamination, which will place human targets in the path of ionizing radiation. Ionizing radiation is dangerous because it has enough energy to knock electrons from atoms, ultimately causing damage to human cells and potentially causing mutations in strands of DNA.

### 1. Ionizing Radiation

The concern with radiation in the context of a "dirty bomb" is ionizing radiation. Ionizing radiation is that radiation capable of freeing an electron from an atom or molecule creating a charged species and free electrons. These particles can go on to interact with other atoms and molecules to create additional charged species. Radiation can be conveniently categorized into the general types: charged particulate radiation, which includes fast electrons and heavy charged particles, and uncharged radiation, which include electromagnetic radiation and neutrons.

Fast electrons include beta particles (positive and negative charge) emitted in nuclear decay. Heavy charged particles include all energetic ions with mass of one atomic mass unit or greater, such as alpha particles, protons, and fission products. The electromagnetic radiation of interest includes X-rays emitted in the rearrangement of electron shells of atoms and gamma rays, which originate from transitions within the nucleus itself. Neutrons generated in various nuclear processes can be further subdivided into slow neutron and fast neutron subcategories.

Ionizing radiation includes a wide range of energies, from10 eV to multiple MeV. The lower energy bound is set by the minimum energy required to produce ionization in typical materials. The upper bound is arbitrary, but is chosen to include energies one might encounter in dealing with radiation dispersal devices. Neutrons can be much lower in energy to have an effect, because of their uncharged nature. Neutrons, however, require separate study and are not usually of direct concern in radiological dispersal devices. Naturally formed isotopes emit only alpha, beta and gamma rays. Neutrons are a concern only in the vicinity of a nuclear reactor or nuclear bomb.

**2. Alpha Particles**

Alpha particles are massive charged particles (4 times the mass of a neutron), and are identical to the nucleus of a helium atom. Because of their size, alpha particles cannot travel far, only about two inches in air, and are fully stopped by the top layer of skin or by clothing. While, alpha particles are negligible as external hazards, they can cause significant cellular damage in the region immediately adjacent to their physical location and consequently are of grave concern when ingested or inhaled. They are assigned a quality factor Q of 20, which is discussed in more detail later.

**3. Beta Particles**

Beta particles are identical to electrons, though they originate from the nucleus and also include an anti-particle partner, the positron. They travel a short distance in tissue, and in large quantities can produce a lesion, called a "beta burn" which can appear similar to a thermal burn. Beta particles are emitted from a radioactive nucleus when either one of two conditions applies. A neutron is transformed into a proton or a proton is transformed into neutron. In the event that a neutron decays to a proton, a $\beta^-$ is released. A $\beta^-$ is physically the same as an electron but the notation is used to designate its origins in the nucleus. In the event that a proton decays to a neutron, a $\beta^+$ is released. A $\beta^+$ is called a positron and is the anti-particle for an electron.

### 4. Gamma Rays And X-Rays

Gamma rays are uncharged electromagnetic radiation like microwaves, visible light or X-rays. However, the frequency of the electromagnetic radiation is much higher than visible light, thus the overall energy is also much higher. Because they are highly energetic, gamma rays pass relatively easily through materials. In addition, due to high penetrability, gamma radiation can result in whole-body exposure.

X-rays that we will consider may simply be low-energy gamma rays emanating from within the nucleus, or be the result of rearrangement of atomic electrons. For most of our discussion we treat X- and $\gamma$- rays similarly.

### 5. Neutrons

Neutrons are uncharged and only emitted during fission or fusion, thus are not of concern in a dirty bomb attack. However, when present, they have significant mass and interact with the nuclei of other atoms severely disrupting atomic structures. Neutrons are assigned quality factors as high as 20.

## E. ENERGY

When a nucleus decays, energy is released. The traditional measurement of radiation energy is the *electron volt* or eV. The eV is defined as the kinetic energy gained by an electron due to its acceleration through a potential difference of 1 volt. The multiples, kiloelectron volt (keV) and megaelectron volt (MeV) are more common in the measurement of ionizing radiation.

Our concern with radioactive sources deals with the production of *ionizing radiation*. If there is insufficient energy to free atomic electrons from their nuclei, the radiation does not have the same potential for causing biological damage. Ordinary visible light is non-ionizing radiation. X-rays are ionizing radiation. Roughly energies of the order of tens of eV and higher can cause ionization.

The SI (metric) unit of energy is the Joule (J), which is a macroscopic quantity. When dealing with nuclear processes, we deal with the energies associated with single nuclear events and the more appropriate unit of energy is the electron volt. In SI units, radiation is more appropriately related to the submultiple, femtojoule (fJ) with the conversions shown in the following table.

Table 1. Table of Useful Energies and Conversions

| Name | Symbol | Equivalent Joules | Equivalent eV | Equivalent Standard |
|---|---|---|---|---|
| femtojoule | fJ | $10^{-15}$ J | $6.241 \times 10^{3}$ eV | 6.241 keV |
| picojoule | pJ | $10^{-12}$ J | $6.241 \times 10^{6}$ eV | 6.241 MeV |
| nanojoule | nJ | $10^{-9}$ J | $6.241 \times 10^{9}$ eV | |
| microjolue | mJ | $10^{-6}$ J | $6.241 \times 10^{12}$ eV | |
| millijoule | mJ | $10^{-3}$ J | $6.241 \times 10^{15}$ eV | |
| joule | J | 1 J | $6.241 \times 10^{18}$ eV | |
| kilojoule | kJ | $10^{3}$ J | $6.241 \times 10^{21}$ eV | |

Damage is caused in the body when bonds between important atoms or molecules are broken. Energy given off during radioactive disintegration, in the form of X-rays or gamma rays is enough to break up essential biological molecules. The energy packets of photons (i.e. microwave, infrared, visible light, x-rays and gamma rays) are characterized by their frequency ($\nu$) and wavelength ($\lambda$) and the product of the two equals the speed of light. $\lambda\nu = c$. The frequency and wavelength determine the energy carried by each discrete photon, $E = h\nu = hc/\lambda$.[5] If a photon has sufficient energy to break an electron from the molecule, the remaining molecule is ionized and a radical results. Radicals can easily interact with other atoms, molecules and other radicals resulting in the formation of unintended molecules.

[5] The symbol h stands for a numerical constant called Planck's constant with the value, $h = 6.626 \times 10^{-34} J\cdot s = 4.135 \times 10^{-15} eV\cdot s$. Whenever Plank's constant or ħ ($h/2\pi$) are used, one is dealing with quantum mechanical concepts and subjects that are on the atomic scale.

## F. RADIATION EXPOSURE AND DOSE

In radiation measurements, two concepts are important for consideration of radiation protection, they are ***exposure*** and ***dose***. Exposure refers to the amount of radiation present in an environment, while dose deals with the amount of radiation a subject absorbs.

### 1. Exposure

The concept of exposure was introduced early in the history of radioisotope research and may be considered analogous to the strength of an electric field created by a point charge. The electric field exists regardless of whether there is another charged particle to feel its effect. Gamma ray or X-ray exposure is expressed using the historical units Roentgen (R), defined as the exposure that results in the ionization of dry air such that 1 R = $2.58 \times 10^{-4}$ C/kg of air. This is equivalent to $1.61 \times 10^{15}$ ion pairs created per kilogram of dry air. (Since the air is ionized, there are an equal number of free charges with the opposite sign.) With average pair formation energy of 34 eV, there is $8.8 \times 10^{-3}$ J absorbed per kilogram of dry air.[ix] This unit was established in 1928 in honor of the discoverer of X-ray radiation, Wilhelm Konrad Roentgen.

The ***exposure*** is therefore defined in terms of the effect of a given flux of gamma rays on a test volume of air. It is a function of the intensity of the source, the geometry between the source and test volume, and the attenuation of the gamma rays between the two.

In many instances, it is necessary to know the ***exposure rate***, which is the amount of radiation per second in a particular spot. The exposure rate, dX/dt, can be related to the activity, $\alpha$, of the source, the distance, d, from the source and a constant, $\Gamma$, defined as the exposure rate constant for a specific radioisotope of interest. Assuming there is no attenuation of gamma rays from source to target, then the following equation applies.

$$dX/dt = \Gamma\alpha/d^2$$

The unit of the exposure rate constant, $\Gamma$, is R $cm^2$ $hr^{-1}$ $mCi^{-1}$. For example $\Gamma_{Cobalt\text{-}60} = 13.7$, $\Gamma_{Iodine\text{-}131} = 2.2$ and $\Gamma_{Iodine\text{-}125} = \sim 0.7$. The values of $\Gamma$ reflect the relative energies of the gamma rays emitted by different radioisotopes. Cobalt-60 emits gamma rays of energy 1.33 and 1.17 MeV; iodine-131, 0.365 MeV; and iodine-125, 0.036 MeV.

In practice, air attenuation would have a much greater effect on exposure because low energy gamma rays are also emitted by the radioisotopes and are more susceptible to attenuation.

The relationship between exposure rate, activity and exposure rate constant shows that activity alone is not a sufficient measure of how dangerous a radioisotope is.

**2. Dose**

Two different materials, if subjected to the same gamma-ray exposure, will in general absorb different amounts of energy. The energy that is absorbed by any type of material is defined as the absorbed dose. The historical unit for absorbed dose is the ***rad***, meaning ***radiation absorbed dose*** and defined as 100 ergs/gram. A rad is defined in the cgs (centimeter-gram-second) system of units. The Systems Internationale, SI equivalent[x] that is especially prevalent outside the United States, is called the gray (Gy) defined as 1 joule/ kilogram. The conversion between the two systems[6] is given by

1 Gy = 100 rad.

Radiation absorbed dose (rad) does not specifically deal with biological damage; it refers only to energy absorbed by any type of material. Biological damage is not solely caused by the energy deposited, but by ionization that creates radicals and can cause chemical reactions to occur. Each type of radiation is associated with a quality factor, Q, which relates absorbed dose to the proper biological effects. To put this concept into perspective 1 Gy or 100 rad, while a significant does to the whole body, is equivalent to

0.24 cal/kg of material or 0.24 mcal/g[7] of material. However, one calorie of thermal energy is required to increase the temperature of one gram of water one degree

[6] The CGS (centimeter-gram-second) system of units is typically used when dealing with electromagnetic or electrostatic systems in which quantities are derived from three dimensions, centimeter, gram and second. The SI system of units is more universally accepted across many fields of discipline in which quantities are derived from four dimensions, meter, kilogram, second, and ampere. 1 meter = 100 centimeters and 1 kilogram = 1000 grams, however there are often non-trivial conversions between the two systems.

[7] The energy conversion is represented in this table. 100 rad is converted to 0.24 cal/kg using appropriate conversion factors and by canceling units. Vertical lines represent multiplication and dark lines show equality.

| | | | | | |
|---|---|---|---|---|---|
| 100 ~~rad~~ | 100 ~~ergs~~/g | $2.4 \times 10^{-8}$ cal | **$2.4 \times 10^{-4}$ cal** | 1000 ~~g~~ | **0.24 cal** |
| | ~~rad~~ | ~~ergs~~ | **~~g~~** | kg | **kg** |

centigrade. Clearly the concept of absorbed dose and simple thermal energy deposition is insufficient to describe the biological effect on the human body.

When the effects of radiation on living organisms are observed, the absorption of equal amounts of energy per unit mass under different irradiation conditions does not necessarily result in the same biological effect. Biological effects are dependent on the alteration of molecules that are caused by ionization and molecular excitations caused by the radiation. The severity and permanence of these changes are related to the local rate of energy deposition along the particle track. This effect is quantified in terms of the ***linear energy transfer, L.***[8] In general the greater the linear energy transfer, the greater the biological effect. The biological effectiveness is expressed by specifying the ***dose equivalent, H***, which is the product of the ***absorbed dose, D***, and a ***quality factor, Q*** that characterizes the specific radiation.

$$H = DQ$$

X-ray, $\gamma$-ray, and $\beta$-radiation have a quality factor of unity (Q=1). Alpha particles have a quality factor of twenty (Q = 20). Consequently for a given absorbed dose, alpha particles could result in a greater biological effect than the same absorbed dose due to an $\gamma$-ray.

The unit for dose equivalent H depends on the corresponding absorbed dose as well as the type of organism absorbing the dose. If the dose, D, is expressed in historical units of the rad and the body absorbing the dose is a human, then the dose equivalent, H, is expressed as ***rem***, or ***roentgen equivalent man***. Under SI conventions, the Sievert (Sv) is the dose equivalent when dose is expressed in ***Gray*** (Gy).[9] For example, an absorbed dose of 2 Gy delivered by radiation with Q of 10 will result in a dose equivalent of 20 Sv.

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[8] The linear energy transfer is nearly identical to the specific energy loss (-dE/dx) which is the energy lost by the radiation as it traverses through the material. Linear energy transfer is the energy deposited locally as the ionizing radiation travels through the material. The difference in energy between the two quantities arises because the specific energy loss includes energy lost through bremsstrahlung emission, which may travel a substantial distance from the particle track before depositing its energy. Linear energy transfer includes only that energy deposited along the ionizing radiation's track.

[9] The units Sievert is named after Swedish scientist, Rolf Sievert (1898-1966) who was instrumental in radiation protection and responsible for initiating Sweden's first radiation protection law in 1941. The Gy is named in honor of Englishman Hal Gray (1905-1965) who worked with Rutherford and contributed much to our knowledge concerning the absorption of gamma rays in matter.

$$H = DQ = (2\ Gy) \times (10) = 20\ Sv$$

The corresponding unit relationship for dose equivalent is similar to that of absorbed dose.

1 Sv = 100 rem.

Using a similar calculation for equivalent dose, the example above in historical units would be 200 rad delivered by radiation with Q of 10 resulting in a dose equivalent of 2000 rem.

## G. BACKGROUND RADIATION

Dose rate is simply the radiation dose per unit of time as in rem/min or Sv/min. The typical background dose rate for a human is about **360 mrem/year** [xi](3.6 mSv/year). Each and every day a person receives a certain amount of radiation from naturally occurring sources. Our bodies are accustomed to receiving this natural radiation, as mentioned earlier; the average amount of radiation received by a person in one year is about 360 mrem. Natural radiation comes from four different sources: cosmic, terrestrial, food, and radon. It is important to note that natural radiation is exactly the same as radiation that comes from man-made sources.

Cosmic radiation comes from our sun and from other outer space sources in the form of positively charged particles and gamma rays. At higher altitudes less atmosphere means more cosmic radiation. The average annual dose due to cosmic radiation is about 28 mrem.

Terrestrial radiation comes from sources in the ground and drinking water, such as radium, uranium and thorium. The amount of terrestrial radiation a person receives is largely dependant on geographical location, however the average annual dose due to terrestrial radiation is around 28 mrem.

Internal radiation due to food sources is a result of naturally occurring radioisotopes that are found in the food we eat. The most common is K-40 (potassium-40), but Na-24, C-14, and Ar-41 also contribute to radiation found in food. The average annual dose from food is around 40 mrem.

Radon is a radioactive gas that is produced by radium and often collects in basements and cellars. Radon is an alpha emitter so it must be ingested to pose any threat, but again because it is gaseous ingestion is relatively easy. The average annual dose caused by radon is 200 mrem.[xii] Radon exposure is the most significant contributor to background radiation but can vary by more than a factor of two depending on geographical location.[xiii] Areas that have higher concentrations of uranium and thorium ores have higher amounts of radon. Below is a map of the United States that shows the concentrations and distributions of radon in air as reported by the EPA.

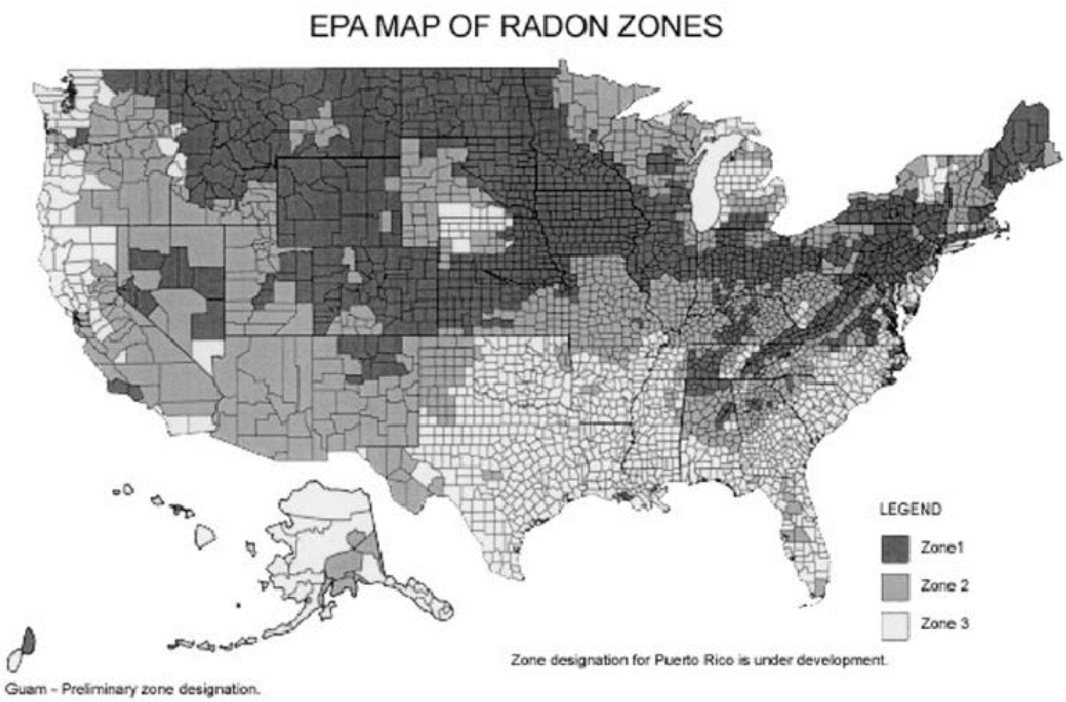


Figure 1. EPA Map of radon zones. **Zone 1** counties have a predicted average indoor radon screening level greater than 4 pCi/L. **Zone 2** counties have a predicted average indoor radon screening level between 2 and 4 pCi/L. **Zone 3** counties have a predicted average indoor radon screening level less than 2 pCi/L. (From Ref.[xiv])

Manmade sources are another contributing factor in the amount of background radiation that the average person receives. Radiation, no matter what the source is, natural or manmade is exactly the same in terms of its effects and properties. Natural radiation does not necessarily mean safe radiation and manmade radiation is not necessarily dangerous. The four major areas of manmade radiation include: medical exposure; atmospheric testing of nuclear weapons; consumer products; and industrial applications. The majority of radiation that comes from medical applications is from X-rays. A typical chest X-ray provides a dose of around 10 mrem, resulting in an average annual dose of 40 mrem. Treating various cancers and other diseases as well as diagnosing and tracking chemicals in the body require radioactive isotopes. As a result of these special techniques, the average annual dose is 14 mrem resulting in a total dose of 54 mrem from medical sources. Atmospheric weapons testing ended in the United States in the early 1960’s and are now banned across most of the world. Nuclear fallout provides very little radiation to the general population, less than 1 mrem. The predominate fallout products include strontium-90 and cesium-137, both with half-lives of around 30 years, meaning more than half the products from the 1960’s are already gone. Consumer products also contribute to a small portion of background radiation. Items such as TV’s, monitors, some old luminous watch dials, and household smoke detectors are sources of radiation. The average annual dose from consumer products is 10 mrem. Industrial sources of radiation include, various gauges, non-destructive testing (radiography), laboratory work, and some mining applications. Industrial exposure is very job dependent and for that matter is not included in the total average annual dose.

The nature of background radiation is very dependent on geographical location, the type of medical treatment you are or are not receiving, and the job that you do. Geographical location is important because of the different soil types in different areas. Some soils contain greater amounts of uranium, thorium and radium than others. High amounts of radium will also mean more radon and uranium and thorium have other daughter products as well. Industrial radiation exposure is dependent on job description. Some people work with machines that use radiation to test welds, evaluate pipe integrity and look for sources of weakness in materials. Other industrial applications include density, thickness, or moisture gauges for production of materials such as papers or plastics or for evaluating moisture content in concrete and soils. It is interesting to note that coal, oil, and natural gas fired power plants provide about twice the background exposure to radiation than do nuclear power plants. The natural occurrence of uranium and thorium is released into the atmosphere when these fossil fuels are burned.[xv] Even people with jobs that are predominately outdoors receive more radiation than those people who work indoors. People who often fly in jet aircraft, such as pilots and business travelers, are exposed to much higher levels of cosmic radiation because higher altitudes mean less atmospheric protection. Below is a table that summarizes the average annual radiation dose for a person in the United States.

Table 2. Sources and Amounts of Background Radiation (After Ref.[xvi, xvii])

| **Natural Sources of Radiation** | Dose per year (mrem) |
|---|---|
| Cosmic | 28 |
| Terrestrial | 28 |
| Food | 40 |
| Radon | 200 |
| | |
| **Manmade Sources of Radiation** | |
| Medical | |
| X-rays | 40 |
| Diagnosis and Treatment | 14 |
| Atmospheric Weapons Testing | <1 |
| Consumer Products | 10 |
| Industrial Uses | Job dependant |
| | |
| Total Average Annual Dose to the General Population | 360 |

## H. INTERACTION MECHANISMS

When radiation interacts with atoms energy is deposited resulting in ionization (or electron excitation). Both **direct** and **indirect** interactions of radiation with cells can occur. Radiation may directly hit a particularly sensitive atom or molecule and cause damage at that location. The resulting damage may be irreparable causing the cell to either die or to malfunction. Radiation can damage a cell indirectly by interacting with water molecules in the body. The energy deposited in the water leads to creation of unstable, toxic hyperoxide ($H_2O_2$, etc.) molecules. These can then damage sensitive molecules and afflict subcellular structures.

## I. EFFECTS OF A RADIATION DISPERSAL DEVICE

In general the population is most familiar with acute high-dose radiation effects, which may occur near nuclear detonations and catastrophic reactor accidents. This will be discussed later, however more pertinent to radiation dispersal devices is low dose-rate radiation. Low dose-rate radiation is also a concern during situations involving industrial contamination.

A radiation dispersal device is a conventional high explosive laced with a radioisotope, not a nuclear weapon. The immediate concern should be the effect of the explosive, followed by that of the radioactivity. The radioactivity will at most produce low dose-rate radiation and at worst late and delayed effects may occur depending on the particulars of the situation. Some possible delayed consequences of radiation injury include: shortened life, carcinogenesis, cataract formation, chronic radiodermatitis, decreased fertility and genetic mutation. The effect upon future generations is unclear. Data from Japan (Hiroshima and Nagasaki) and Russia (Chernobyl) have not demonstrated significant genetic effects in humans.[xviii]

Damage done by gamma radiation at low dose rate or in fractions over a long period of time allows tissues to repair. For example, radiation treatment for cancer is not done at one time, but in a series of sessions. A tumor is more sensitive to radiation than healthy cells, so as the treatment is carried out, the tumor shrinks in size while the normal healthy tissue is allowed to repair. Damage resulting from neutron radiation, such as that resulting from a nuclear weapon, does not however appear to be dose-rate dependent. This is because of the high linear energy transfer of neutrons that cause disruptions that are locally much greater than gamma radiation, and repair mechanisms are hindered.

Data pertaining to the type of effects one might expect from a dirty bomb may be obtained from experiences learned from Soviet nuclear weapons production.[xix] In such a setting, annual doses of 2 to 4.5 Gy were received by the workers equivalent to doses on the order of 200 to 450 rem. If this type of dose were delivered within a very short period of time, on the order of a minute or less, and no immediate medical treatment were given, the survival rate of the dose recipient would be about 50 %. Below is a table that summarizes the effects of an acute whole body dose.

Table 3. Biological Effects of an Acute Radiation Dose to the Whole Body (From Ref.[xx])

| **Dose** rem (Sv) | **Biological Effects** |
|---|---|
| 0-50 (0-0.5) | Little obvious effect except for possible minor blood changes |
| 80-120 (0.8-1.2) | Vomiting and nausea lasting for about 1 day in 10% of exposed individuals. Fatigue but no serious disability. |
| 130-170 (1.3-1.7) | Vomiting and nausea in nearly all exposed individuals within 2 days, followed by other symptoms of radiation sickness in 25% of individuals exposed. No death is expected with treated individuals |
| 180-220 (1.8-2.2) | Vomiting and nausea in nearly all exposed individuals within 1 day, followed by other symptoms of radiation sickness in 50% of individuals exposed. Up to 20% of untreated individuals die. |
| 270-325 (2.7-3.25) | Vomiting and nausea in nearly all exposed individuals within 1 day, followed by other symptoms of radiation sickness. Up to 50% of untreated individuals die within 2 months. Survivors require 6-month recovery. |
| 400-500 (4-5) | Vomiting and nausea in nearly all exposed individuals within 1 day, followed by other symptoms of radiation sickness. More than 50% of untreated individuals die within 2 months. Survivors require 6-month recovery. |
| 550-750 (5.5-7.5) | Vomiting and nausea in nearly all exposed individuals within 4 hours, followed by other symptoms of radiation sickness. Nearly all untreated individuals die with in 2 weeks. |
| 1000 (10) | Vomiting and nausea within 1 to 2 hours. Untreated patients probably do not survive |
| 5000 (50) | Almost immediate incapacitation. All exposed individuals will die, most within 48 hours. |

In Soviet weapons production, the dosage was obtained over the course of a year. Diagnosis of chronic radiation syndrome (CRS) was observed in 1596 workers. CRS is marked by leukophenia (both netrophils and lymphocytes depressed) and thrombocytopenia. In severe cases, anemia, atrophic changes in the gastrointestinal mucus membranes, encephalomyelitis, and infectious complications due to immune depression were noted.

CRS is highly unlikely to affect first responders because exposures over a short period of time are not linked to CRS. 4.5 Gy over a full year implies a dose rate of 0.51 mGy/hour or 51 mrem/hour, continuously. In this type of situation, the numbers imply that access to the contaminated area be restricted and personal working in the area be carefully monitored as to their accumulated dose.

Near ground nuclear weapon detonation, radiation dispersion devices, major reactor accidents, or similar events that create contamination with high dose rate would permit development of CRS if the exposure were prolonged. Evidence from the former Soviet Union suggest that once the patient is removed from the radiation environment clinical symptoms slowly resolve themselves and complete recovery is possible when the dose rate is low.

As seen in this discussion, in the case of an RDD incident, the first responder will be in the area for much less than a fraction of a year so the main concern is to respond to the physical effects of the explosive device.

Statistically, an individual already has a relatively high risk of developing cancer; in the United States it is about 20%. The background risk of cancer makes it difficult to determine what the risk of cancer is resulting only from radiation exposure. Exposure to 100 mGy gamma radiation (twice the U.S. occupational annual limit of 0.05 Gy (5 rad)) causes the lifetime risk of death due to cancer to increase 0.8 %. Thus, if 5000 individuals are exposed to the expressed 100-mGy level, as might be possible in a rescue operation, the fatal lifetime cancer rate may increase from 1000 in the group to 1040.[xxi] However, these are statistical estimates and in that population the uncertainty in the number susceptible to lifetime cancer is +/- 30. Extrapolating further, exposure to the U.S. general public annual limit of 100 mrad per year above background levels would increase the probability of contracting cancer by 0.008 %, less than a single individual in our population of 5000.

### 1. Psychological Effects

Radiation illness symptoms in a few first responders can have a devastating psychological effect on the entire first responder crew. This acute anxiety has the potential of becoming the dominant concern of the crew and detracts from attention to other hazards. Psychological effects can greatly increase the potential of injury from conventional hazards.

The same applies to the general public in the area.

The severity of the psychological effects of an RDD will depend on the nature of the RDD material and upon the method of deployment. The physical injury sustained from a RDD may be due only to the blast, but misinterpretation of the explosion as a nuclear detonation may induce fear similar to that produced from a true nuclear detonation. Mass psychosomatic symptoms due to unrealistic fear of the effects of radioactive material may be pervasive and may severely overload medical support operations.

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# III. RESPONDING TO RADIATION THREATS

## A. RADIATION THREAT SCENARIOS

First responders must be prepared to adequately treat injuries complicated by ionizing radiation exposure and radioactive contamination. In most scenarios, the radioactive contamination containment will provide a bigger challenge than the immediate radiation effect.

Nuclear detonation and other high-dose radiation situations are the most critical, though least likely, events for concern. Acute high-dose radiation may occur in three situations: first, a nuclear detonation that produces extremely high dose rates from radiation generated during the initial minute (prompt radiation) as well as from fission products in the fallout area near ground zero; a nuclear reaction which results if high-grade nuclear materials are allowed to form a critical mass, releasing large amounts of gamma and neutron radiation without a nuclear explosion; finally, a radioactive release from a radiation dispersal device (RDD) made from highly radioactive material such as cobalt-60 can result in a dose sufficient to cause acute radiation injury.[xxii] Although many of the considerations in this report are applicable to the first two situations, our concern is with the third, the radioactive release from a RDD. Acute effects are considered a worst case for an RDD event. In most cases the radiation is too dispersed to pose an acute threat and even the initial amount of radioisotope may be too low to pose a significant acute threat.

An RDD is any dispersal device causing purposeful dissemination of radioactive material across an area without a nuclear detonation. Parties with conventional weapons and access to radionuclides can develop an RDD. RDDs cause conventional casualties to become contaminated with radionuclides and complicate medical treatment and evacuation from the area.

A discussion of radiation threat scenarios needs to recognize what is common with and what is different between each of the three types of events. The medical consequences of radiological events are extrapolated from what we know from nuclear detonations and reactor accidents, most notably the effects from the atomic bomb in

Hiroshima and Nagasaki and from the reactor accident at Chernobyl. In the event of an RDD attack, one needs to recognize the difference in magnitude between such an attack and bombs or reactors. Most contemplated RDD scenarios are orders of magnitude smaller than those occurring during a nuclear bomb or major reactor accident.

## B. EXPLOITABLE RADIOACTIVE SOURCES

Radiation sources that may be exploitable for use in a radiation dispersal device include, but are not limited to: sources related to medical diagnosis and therapy; those obtained from the nuclear fuel cycle and reactors; those used by academia and research facilities; sources used by industry; various components of weapons systems; naturally occurring and consumer product sources. Natural sources and some consumer products only pose a major threat when they have been processed for use. These sources typically have longer half-lives and thus less specific activity. The most likely sources of radioactive isotopes are those used in industrial and medical applications. Isotopes such as strontium-90 and cobalt-60 have applications in generators and food irradiation, while cesium-137 and cobalt-60 are used in different types of gauges and in medical treatment. These sources are discussed in more detail later in this report.

## C. TYPES OF RADIATION EFFECTS

Generally, two types of radiation exposure exist. Those that result in external exposure in which irradiation comes from a source outside of the body and those that result in contamination in which radioactive material comes in contact with the body or enters the body. Contamination and external exposure are not necessarily exclusive, they may occur together.

By simply removing the victim from the vicinity of an external source or by shielding the source, exposure is greatly reduced or even eliminated. The caregiver or first responder is not in danger of receiving a radiation dose from the victim because external exposure does not create a secondary source of radiation. The victim does not become radioactive and does not pose a threat to other individuals.

Contamination, on the other hand, results when a victim's body has radioactive materials on or in it, making the victim a source of radiation. Internal contamination can result from inhalation, ingestion, direct absorption through the skin, or penetration of radioactive materials through open wounds. External contamination may be the result of materials being deposited by direct contact with the source or by radioactive materials spread by the explosion. When dealing with contamination, the caregiver or first responder may need to approach the situation quite differently.

## D. EXTERNAL CONTAMINATION

The first responder may come in contact with radionuclides in the vicinity of an RDD incident, and become externally contaminated. However, if an individual is wounded in a contaminated area, he may become an internally contaminated patient. The radiation hazard of the injured personnel to both patient and attending medical personnel will be negligible, so necessary medical or surgical treatment should not be delayed because of possible contamination. Unlike chemical contaminants, radiological materials active enough to be an immediate threat can be detected at great distances.

Radiation detectors can easily locate external radioactive materials. The most common contaminants will primarily emit alpha and beta radiation whose range is short, so protective clothing will easily shield the body from their effects. Beta emitters when left directly on the skin will cause significant burns and scarring. Alpha radiation will not penetrate the outer layer of skin. External contamination of the skin and hair is particulate matter than can be washed off. It is usually not possible for a patient to be so contaminated that he is a radiation hazard to health care providers.

Simple hygiene can prevent beta-induced skin ulceration and is rare in climates where people are fully clothed (arms, legs and neck covered). Washing off contaminants can prevent beta skin damage. If practical, the effluent should be sequestered and disposed of separately and appropriately. However, in treating patients, concern about radioactive contamination should be secondary to treatment for physical injury. The table below presents the degrees of radiation dermatitis for local skin area radiation doses.

Table 4. Dose Effects on Radiation Dermatitis (From Ref.[xxiii])

| | Dose (Sv) | Dose (rem) | Effect |
|---|---|---|---|
| **Acute** | 6-20 | 600-2000 | Erythema only |
| | 20-40 | 2000-4000 | Skin breakdown in two weeks |
| | >3000 | >300000 | Immediate skin blistering |
| | | | |
| **Chronic** | >20 | >2000 | Dermatitis with cancer risk |

As can be seen in the table above the beta doses required for significant skin effects are considerable. Proper hygiene will prevent skin damage effects. **It is important to understand that simply being exposed to radiation does not make a person radioactive.** However, if a person walks in, breathes, or in any way touches contamination there is a potential for that person to become contaminated, either externally or internally. Once a person is contaminated, they are constantly exposed to radiation and its effects.

### 1. Decontamination

Decontamination is usually performed during the care of the patient by emergency service and, ideally, prior to arrival at medical facilities. This may not always be practical. However, it should be recognized that simple removal of outer clothing and shoes might effect a reduction of greater than 90 % of a patient's contamination.

The presence of radiological contamination can be readily confirmed by passing a radiation detector (radiac) over the entire body. Open wounds should be covered prior to decontamination. Contaminated clothing should be carefully removed and placed in marked plastic bags. Bare skin and hair should be thoroughly washed, and the effluent should be sequestered. Both contaminated clothing and effluent should be stored in a secure location within a contaminated area for later appropriate disposal or analysis.

Radiological contamination should never interfere with medical care. Unlike chemical agents, radioactive particles will not cause acute injury and decontamination that is sufficient to remove chemical agents is more than sufficient to remove radiological contamination.

## E. INTERNAL CONTAMINATION

Internal contamination results when radioactive material is introduced into the body by inhalation, ingestion, or by absorption through the skin. The first responder cannot easily determine if internal contamination has occurred unless it is relatively high. Even if internal contamination is detected, it cannot be readily addressed at the scene. Internally contaminated individuals must be moved to a medical facility for treatment. Radionuclides react with the body chemically in the same way that the stable isotopes react with the body. For example, strontium-90 is chemically similar to calcium, thus it tends to collect in the bones. Iodine-129 and iodine-131 are taken up by the thyroid and cause damage there. Both isotopes of iodine are produced as products of fission reactions either in reactors or in nuclear detonations and as such are not a real concern for RDDs.[10]

The biological interactions that result as a consequence of internal contamination mean that special chemical and physical treatments are needed. These treatments may only be available at a medical facility. Gastric lavage is effective within the first two hours of uptake; antacids can reduce absorption, those containing aluminum are especially effective against strontium; cathartics can be used to minimize radiation time in the bowel. Other chemical treatments include Prussian blue[xxiv] to combat cesium; chelating agents including DTPA (diethylenetriaminepentaacetate) or EDTA[xxv] (ethylenediaminetetraacetic acid) are used for some metals, such as americium and other transuranics; aluminum phosphate or barium sulfate can also be used for strontium ingestion.[xxvi]

[10] Potassium iodide tablets are often stated to be the universal treatment for internal radiation contamination, however they are only useful in combating radioactive iodine such as I-129 or I-131. I-131 has a half-life of around 8 days, which is too short lived to be feasible as an RDD weapon and I-129 has a half-life of 16 million years, which decreases its specific activity and effectiveness as an RDD weapon.

## F. DETECTION AND INSTRUMENTATION

Radiation is not detectable by human senses; it does not have a distinctive smell or taste, and it cannot be seen or felt. Though an extremely high dose of beta radiation may feel hot, there is nothing to indicate that the source of the heat is in fact radiation. The consequence of radiation's escape from human detection is that an RDD event cannot immediately be classified as such. Radiation dispersed by a dirty bomb or by some other means must be identified as quickly as possible to facilitate appropriate response. Some type of instrument is needed to assist the first responder in determining if radiation is present and if so, to what level.

There are many types of instruments with varying size and capability. Some detectors simply clip on to external clothing and record overall exposure while others belong in the laboratory and provide a full spectrum of information about a sample. The first responder needs something in between: an instrument that is simple to use, reliable, and alerts the user to dangerous levels of radiation. Instruments that might be useful to first responders include electronic dosimeters, personal radiation alert systems, and isotope identification units.[xxvii]

A dosimeter is a device that records the radiation dose received by the user over a period of time. A thermoluminescent dosimeter (TLD) is a device that contains a piece of radiation sensitive material and must be processed to render information about exposure. These devices are generally called film badges. An electronic dosimeter uses silicon chips or Geiger-Muller tubes[xxviii] to provide an instantaneous warning. Electronic dosimeters are useful in that they immediately detect large amounts of radiation and protect from overexposure, and operate over a wide range of exposures using little power.[xxix] There are some models that offer very small sizes though they compromise on detection range and overall features.[xxx] Other instruments are built to military specifications and may be useful to first responders facing similar harsh environments.[xxxi] These devices alone may not be enough to detect the use of an RDD because the radiation is dispersed and may not be strong enough, however they are useful for providing an easy to understand warning.

Personal radiation alert systems are more sophisticated than electronic dosimeters in that they are much more sensitive and can locate smaller amounts of radiation. They detect radiation using a method known as scintillation.[xxxii] Scintillation depends on a sensitive material that responds to incident radiation. The response of the material can be measured and calibrated to indicate the appropriate level of radiation. These systems are very sensitive and as such do not work well in a high dose region. Personal radiation alert systems are useful for determining if a dirty bomb has been detonated but may not appropriately alert the user to a dangerous situation. These devices are more suited to inspecting with greater sensitivity, though greater sensitivity means the unit is larger than a pocket device.[xxxiii] More training is required for the proper use of these tools in order to understand the information that the instrument provides. Misinterpretation of the instrument may mean that victims are not properly cared for.

Isotope identification units are also very sensitive and would be useful in some situations. These instruments can detect changes in the background level of radiation. However, because of their complexity and the type of information provided, in general, they require extensive training or experienced personnel to be used properly. A few instruments of this type are available that require limited training and offer other operator friendly features.[xxxiv] The advantages of this class of instruments are that they can, with relatively good reliability, determine which isotopes are present. Using gamma spectroscopy[xxxv] and a built in database of spectra the instrument is able to provide isotope data. Gamma spectroscopy relies on the gamma energies given off by most radioactive isotopes. Each isotope radiates with unique gamma energies. When taken together a spectrum of energies is produced resulting in a unique “fingerprint” for each isotope. Some instruments have detectors based on sodium iodide crystal[xxxvi] that can be more effective than germanium detectors and reduce exposure to the user.[xxxvii] These instruments are generally expensive, though not prohibitively so on the regional level. They are valuable to the first responder however. They can identify the isotopes likely to be used in a dirty bomb, which can aid in directing the response and treatment of individuals.

Responding to an RDD event or a dirty bomb hinges on the ability to accurately and effectively determine that such an event has occurred. Radiation is not detectable by human senses and the symptoms of radiation exposure may not immediately suggest such exposure. As a result, instruments are needed to detect and identify radiation and radioisotopes. Instruments are also needed to provide safety to first responders and give them the confidence needed to appropriately attend to casualties. In the event of a dirty bomb, blast effects pose the greatest threat to the victims and not responding because of lack of detection instrumentation or misunderstanding of the tools should not be an issue. This section is not meant to be a recommendation as to what instruments are appropriate for a given situation, merely a review of some tools that are available to the first responder. Need as well as cost will determine what type of instrument is appropriate. Instrumentation is an important aspect in responding to an RDD event, however it is not enough. Understanding how to use the instrument and the information it provides results in the most effective response.

# IV. CASE STUDIES

## A. INTRODUCTION

By studying historical events involving radiation dispersal and procurement of such materials, a better understanding of the nature of future events may be gained. The response of the public as well as that of first responders highlights some of the issues unique to RDD and dirty bomb events. Goiana, Brazil, the second largest radiological disaster after Chernobyl, illustrates what may happen if contamination is spread unbeknownst to the public and how fear and chaos result. Izmailovsky Park, Russia was an actual malicious event, while Georgian woodcutters were accidentally exposed to abandoned material that could have been obtained for nefarious intentions. Also included are a number of cases involving stolen Russian uranium. While, uranium is not a viable isotope for a dirty bomb, it is highly sought after because it is a necessary component for a nuclear weapon. Many of the isotopes useful for dirty bombs are not as highly protected as uranium is, as a result may be easier to obtain. These cases should be considered as examples and extensions of the potential realities of an RDD event. Following this section, possible RDD scenarios are considered and analyzed based in part on information from historical cases.

## B. GOIANA, BRAZIL 1987

In September of 1987 an accident involving cesium-137 caused panic and contamination in the city of Goiana, Brazil. The event, while an accident, demonstrates how a radioisotope may be obtained and what the results of radiological dispersion are. An abandoned radiotherapy unit containing cesium-137 was scavenged from a deteriorating hospital facility. Scavengers thought they would make some quick money by scrapping the machine at the junkyard. Instead, while dismantling the equipment at the junkyard, the cesium container was broken and the radioactive cesium (1400 curies) was released. Unbeknownst to those dismantling the machine was the dangerous situation they had just created. Portions of the source were given to members of the junkyard owners' family because of the blue glow that it gave off in the dark. The glow enticed some people to spread the cesium on their skin because of the resulting appearance. One six-year-old girl “rubbed the powder on her body so that she glowed and sparkled” and later ate a sandwich with her contaminated hands.[xxxviii]

It was not until a week after the cesium container was initially pried open that authorities became aware of the radiation leak. The Brazilian Nuclear Energy Commission responded and discovered that 244 people had been contaminated, of those 54 had to be hospitalized. At the time, the nearest radiation treatment center was at the Navy hospital in Rio de Janeiro, 600 miles away from Goiana. Ten people had to be airlifted to the Navy hospital. A medical team sent by the International Atomic Energy Agency (IAEA) also responded to the situation and discovered that 20 people had been internally contaminated, by inhalation or ingestion. As a result of the internal contamination, individuals received doses from 100 to 800 rad. The internally contaminated patients were treated with a chemical know as Prussian blue (ferric ferrocyanide), an iron compound known to complex with cesium and aid in the removal process. Treatment with Prussian blue was largely effective despite the more than one-week delay in recognizing the problem. Because of its similar chemistry, cesium readily displaces potassium in the cells and causes damage there. As a direct result of internal contamination, four people died including the six-year-old girl.

Over 34,000 people were processed at the city’s Olympic soccer stadium and examined with survey meters to screen for contamination. Only around 250 of the more than 34,000 people were contaminated, illustrating the concern even an accidental radiological dispersion causes. How much more would the panic and concern be in the event of a malicious radiological dispersion event? Though this was a very large-scale incident, many of the technicians who were screening people did not wear any type of protective equipment, and decontamination of the ambulances was also neglected for a number of days. Three different junkyards and one home were determined to have the largest amount of contamination, while 85 other homes were also contaminated as well as much of the downtown area of the city. Nearly half of the contaminated homes were evacuated, some even demolished. Some of the contamination was able to be removed, however a great deal of debris was stored in concrete drums and disposed as nuclear waste. The cost of cleanup was tremendous, but the long-term economical impact to the downtown area is undetermined.

## C. IZMAILOVSKY PARK, MOSCOW, RUSSIA 1995

On November 23, 1995, a package that contained cesium-137 was discovered hidden under a bench in the popular Izmailovsky Park in Russia. The package weighed about 32 kg, however, the majority of the weight was likely shielding. The source of the cesium-137 is likely from a medical instrument or industrial gauge. A reporter from Russia's Independent Television Channel, responding to a tip from Chechen rebel leader Shamil Basayev, discovered the package. The cesium-137 was not linked to any explosive nor was any local contamination indicated. However, undiscovered the cesium-137 could have affected thousands of people passing through the busy park for weeks or months. This event demonstrates the willingness of terrorist to use radiological sources as well as the reality of obtaining such sources.

## D. INGURI RIVER, NORTHWESTERN ABKHAZIA, GEORGIA, 2001

In December of 2001, a group of three Georgian woodcutters working in a remote forest discovered an orphaned Soviet era radiothermal generator (RTG). RTGs were used by the Soviets as power sources for radio communication equipment and navigational beacons positioned in remote locations. Soviet RTGs are powered by radioactive strontium-90 or cesium-137, and typically contain about 40,000 curies of activity. The entire unit is about 60 to 120 cm in length while the actual radioactive core is about the size of a flashlight and is completely surrounded by lead shielding. Electricity is generated when a transformer converts the heat produced by beta particle collision with a titanium based ceramic sheath heated to more than 900 degrees Fahrenheit. Typically, RTGs do not pose a radiation threat when the lead shielding is intact, but over the years since the Soviet break up, many derelict units have been lost, damaged, or are simply unaccounted for.

It was one of these derelict RTGs that the Georgian woodcutters discovered in December of 2001. The heat from the RTG had melted the snow and revealed itself to the men. Employing the heat from the RTG, the men settled in for the night. Quickly, the men grew sick and became dizzy and soon noticed the effects of beta-burn, red peeling skin. While the beta particles were causing external burns, gamma rays caused excessive internal damage to organs. One man recovered in three months, two others remained in critical condition after that same time period.

The International Atomic Energy Agency (IAEA) responded to the reports of the abandoned RTGs and found two in the area where the woodcutters had been. Four other strontium-90 generators were found in Georgia, which the IAEA believe are the final lost generators in that country. Truly, there is no way of knowing if or when all the generators will be accounted for. Russia's Ministry of Atomic Energy has indicated that a factory in Estonia produced over 900 RTGs during the Soviet era, some that are five times as powerful as the ones the woodcutters discovered.[xxxix] There are presently still hundreds of RTGs that are unaccounted for, predominantly in remote areas of Russia and former Communist States. Again, the woodcutters discovered the strontium-90 generator by accident and did not know what it was, but a terrorist looking for a ready source of radioactivity may have to look no further than a lost RTG.

## E. STOLEN RUSSIAN URANIUM

While uranium-235 is not particularly useful for radiological dispersion devices, it is highly sought after because it is a fissionable material. As a result, facilities that use U-235 generally have a much higher level of security. Much of the material that is stolen or scrupulously obtained comes from Russia or Eastern European sources control is less active. The following three cases describe how various amounts of U-235 were obtained, but could also be applied to other isotopes, or facilities.

### 1. Andreeva Guba Naval Base

On July 29, 1993, 1.8 kg of uranium fuel rods (36% U-235) were stolen from Andreeva Guba Naval Base on the Kola Peninsula in Russia. Two men that worked at the base, the guard and another sailor, were able to cut the alarm wire that ran down a hallway and move undetected to the storage area where the lock was pried off with a metal bar. Two fuel rods were taken and the men removed the uranium and cached it in the woods outside of the base. The men eventually confessed and the fuel rods were recovered. This facility, like most, keeps outsiders out but does little to prevent personnel from moving freely about the base and acting outside of imposed security measures. This type of theft seems most probable for obtaining isotopes considering the potential financial gain, and the easy access of the insiders.

#### 2. Sevmorput Naval Shipyard

On November 27, 1993, 4.5 kg of uranium fuel rods (20% U-235) were stolen from the Sevmorput Naval Shipyard in the northern part of the city. Two officers, Aleksei Tikhomirov and Oleg Baranov drove to the base to execute a plan developed by the younger brother of Tikhomirov, Dimitri, who worked at the base. Tikhomirov cut a hole in the fence while Baranov waited in the car. Tikhomirov was able to saw through the lock on the storage bunker, pry the door open, and remove the uranium from three fuel rods. Both men easily escaped with the uranium and the theft was not discovered until the next afternoon. Had Tikhomirov not forgotten to replace the lock as planned, the theft probably would have been left undiscovered for a long time as the bunker contained hundreds of fuel rods to conceal the absence of three. The men eventually slipped up while trying to sell the uranium and the material was recovered. Again, inside knowledge of the shipyard and inadequate security led to the success of this theft.

#### 3. Yuri Smirnov and Luch Scientific Production Association

In May of 1992, Yuri Smirnov began stealing highly enriched uranium (90% HEU) from Luch Scientific Production Association, the factory he worked at. Smirnov worked in a laboratory that did research for spacecraft reactors and so had daily access to highly enriched uranium. In 1992, as massive inflation hit the Russian economy, Smirnov decided to pad his salary by selling uranium when he learned about the street value from a newspaper article. Despite the internal controls on the uranium, which factored in a 3% book loss of material, Smirnov was able to skim about 1% of the uranium he worked with by being extremely careful. A couple of times each month he would walk out of the factory with a 50 g vial of HEU. His coworkers never suspected the loss of material, nor did they ever see him taking any uranium. The factory did not have any detectors at the exits and each worker was individually responsible for checking his own hands for contamination.

When Smirnov decided that he had collected enough uranium, a final mass of 1.532 kg, he began his plan to sell the uranium. The plan included storing the uranium in a locker at one of the train stations in the city. Unfortunately for him, when he was transporting the uranium to the station he met some drunk neighbors on the platform who recognized him and began to talk. In an unrelated incident the police were after the neighbors and so arrested everyone in the group. It was not until they had reached the police station that they discovered the true identity of the material in the lead lined containers. While 1.5 kg is not enough HEU to produce a nuclear weapon, it is a poignant example of how even materials that should require strict security measures can escape from those controls.

# V. POSSIBLE SCENARIOS

## A. INTRODUCTION

In recent times, with the increasing possibility of an RDD or dirty bomb attack, more and more effort has been taken to create scenarios that allow for analysis of such attacks. Numerous governmental and independent agencies have worked together to play out these scenarios either on paper or in reality. Using these scenarios as a preparation tool and for risk assessment provides first responders with an understanding of not only their specific role but a view of the whole picture. The Federation of American Scientist (FAS) presented their findings on three specific scenarios to the Senate Committee on Foreign Relations on March 6, 2002.[xl] The Center for Strategic and International Studies (CSIS) analyzed a simulation of a 4000-pound dirty bomb in March of 2004.[xli] Between May 12 and May 16, 2003, the Department of Homeland Security conducted the largest terrorism response exercise to date in the United States, including a scenario that involved an RDD attack on the city of Seattle.[xlii] The event was known as TOPOFF 2 for Top Officials Exercise Series. On November 14, 2002, the county of Los Angles ran an exercise known as Operation Critical Response involving the use of RDDs.[xliii]

A simulation and resulting analysis by the Center for Strategic and International Studies again confirmed the most generally accepted results of a dirty bomb attack. In March of 2004, CSIS simulated the detonation of a 4000-pound dirty bomb loaded in a school bus parked outside of the National Air and Space Museum.[xliv] The museum was almost totally destroyed by the blast with neighboring buildings experiencing damage as well. CSIS estimated there were 10,000 people in the immediate area at the time of the blast, but were unable to give a casualty estimate. They did agree to the extent of immediate casualties, however both deaths and serious injuries were due to the blast effects. Contamination did spread as far as southern Pennsylvania, though the worst was localized to a few blocks. Individuals located in the area of highest contamination received a dose of about 5 rem in one hour, equivalent to the occupational dose for one year set by the EPA and NRC.[xlv] A person outside of the most contaminated areas, out to about a mile away, would require weeks of exposure to exceed the recommended yearly dose. The simulation performed by CSIS produces and confirms the most accepted effects and risks associated with a dirty bomb attack

What follows now is a summary of additional scenarios and models, including the general results and analysis provided in the report. This paper also discusses the feasibility or likelihood of the proposed scenarios and presents some conclusions. Conclusions are made by looking at the analysis within the report itself and in conjunction with independent analysis and historical cases. The scenarios presented by the FAS are the most specific and relate to actual radioactive material, while the TOPOFF 2 exercise and Los Angles County's Operation Critical Response deal more with first responder coordination and items of general concern when dealing with an RDD.

## B. FEDERATION OF AMERICAN SCIENTISTS REPORT

As described earlier, Henry Kelly from the Federation of American Scientist testified before the Senate Committee on Foreign Relations. In his testimony he describes why dirty bombs pose a threat to the American population as well as how a person might obtain the necessary materials to build a dirty bomb. He also outlines three potential scenarios involving different sources of radioactivity and analyzes the results of such attacks. Following, is a summary of the FAS determination of a dirty bomb threat along with their conclusions. In addition, this paper further explores each scenario and describes the feasibility and potential danger of such attacks.

In introducing his presentation to the Senate Committee on Foreign Relations, Henry Kelly makes three conclusions about dirty bombs in the United States. First, that radiological attacks constitute a credible threat because of the many under secured sources located at sites across the country, as well as the ease of dispersing the sources in an urban area. Second, that such an attack would result in some deaths (from radiation exposure), but contamination would affect large urban areas beyond EPA guidelines. Finally, those areas on the order of tens of city blocks would face contamination levels that would cause even a small number of radiation casualties and would require immediate evacuation and cause widespread fear. Demolition may be the only feasible remedy and in a place such as New York City, the cost could mount into the trillions of dollars.

Radioactive isotopes are commonly used in a variety of consumer and industrial products. From cancer treatment, food and medical sterilization, oil exploration, smoke detectors, to laboratory research, isotopes are important for doing specific work. For this reason, there are many sources of isotopes available to the terrorist that may or may not be well secured. Cobalt-60 and cesium-137 are gamma sources used to kill cancer cells and bacteria, but can also harm normal human cells. Americium-241 and plutonium-238 are alpha sources, which only pose an internal hazard to the human body. Americium is used in the fabrication of smoke detectors and for locating oil under ground. Plutonium, while being a fuel for some power reactors and for nuclear weapons, it is often used in laboratory research as well. Typically, there is strict regulation of these types of sources, but when their usefulness declines, so do the appropriate security measures. Even in the United States, sources have been left in junkyards, buildings and vehicles.

The FAS, because of likely availability of the necessary isotopes, chose the following scenarios for evaluation. Americium is taken from a well-logging source, cesium from an abandoned medical gauge in North Carolina, and cobalt from a food irradiation facility. The actual effects of any scenario depend largely on the amount of material used (both conventional explosive and radioactive isotope), the strength of the material, the direction and speed of the wind as well as other weather characteristics, the size of the particles which would affect how well they are carried by the wind or inhaled, and the size and location of nearby structures. FAS estimate that their scenario predictions may be too high or low by a factor of ten. Assumptions for the scenarios include: a calm day with wind speed less than one mile per hour; distribution is by explosion that creates a mist of fine particles that spreads downwind; and that people are exposed to radiation in different ways. Exposure is by initially inhaled dust, the assumption being that 20% of the material is small enough to be inhaled; by continuous inhalation of material that has settled but is kicked up by wind, cars, or pedestrian movement; and by contaminated food and water sources in rural areas. Guidelines for response are based on EPA procedure, including evacuations and medical attention.

Decontamination by sandblasting or demolition that cannot reduce cancer danger to under one-in-ten thousand means the area would have to be abandoned.

### 1. Americium-241

The scenario involves the release of Am-241 obtained from a mining or well-logging application detonated with one pound of TNT. The FAS scenario does not specify the strength of the source used in their analysis. A typical well-logging source is from 3-20 Ci[xlvi] in strength. Based on the loss of a well-logging source around February 4, 2002 by BNP Petroleum, this analysis assumes a source of 16 Ci of Am-241.[xlvii] FAS estimates that people in an area ten times that of the blast area would require medical attention (based solely on radiation exposure, not blast affects), while an area 300 times that of the blast area would need to be evacuated within one half an hour. Initial inhalation and subsequent inhalation would pose the greatest threat and people within a two-block radius of the blast would have a cancer death probability of one-in-a-thousand.[xlviii] An area of about sixty blocks would be contaminated beyond EPA standards.

Am-241 is used in oil well-logging applications because when combined with stable beryllium (Be), it produces a constant flux of neutrons.

$$^{241}Am(\alpha) + {}^{9}Be \rightarrow {}^{12}C + n^{o}$$

The neutrons are used for neutron activation analysis (NAA), which relies on neutrons to create radioactive species in the rock and soil that in turn produce a characteristic spectrum.[xlix] Americium is the most commonly used source, but radium-226 and plutonium-238 in combination with beryllium have also been used.[l] All of these isotopes are sources of alpha particles.

Table 5. Americium-241

| | |
|---|---|
| Specific Activity | 3.428 Ci/g |
| Half Life | 432 yrs |

The Am-241 proposed in this scenario is a 16 Ci source with a mass of 4.665 g.

This source would be easily shielded due to the low energy gamma emission and the alpha particles. Anything that shields the gammas is enough to contain the alphas. In this case a very thin piece of lead or other dense metal would shield the gamma energy. When dealing with gamma rays, shielding is used to reduce the amount or flux of the energy. Shielding material does not change the magnitude of the energy, however the flux is reduced in an exponential manner. Lead is often used as a standard material to reference the amount of shielding needed to reduce the flux by 10 or 100 times.[li] In reality many types of materials are used depending on the application and cost. In large reactors and laboratories, many feet of concrete and steel constitute the majority of shielding.

Inhalation of dispersed particles would be the most dangerous aspect in this scenario, because of the longer half-life of Am-241 and the alpha particles could then interact internally with the body. Alpha particles have a high linear energy transfer and thus lose most of their energy in a very short distance; as a result the outer layers of skin easily shield them. Internally, however, large amounts of energy are directly deposited in one area.

There have been cases where an Am-241 source has been lost, sometimes during transportation, as was the case on April 5, 1978 when a 2.8 Ci source fell off of a truck in transit to a job site. The source was later recovered 110 miles from the facility by a highway construction worker, 15 feet from the road.[lii] Sometimes the source is lost thousands of feet below the surface of the earth and not readily available to terrorists, as was the case with BNP. In 2002, BNP Petroleum lost a 16 Ci Am-241 source while drilling on Padre Island, Texas. The source was unrecoverable and left at a depth of about 10,500 feet and capped with a concrete plug.[liii]

Another ready source of Am-241 is smoke detectors. Based on readily available product information, the typical detector contains about 1 μCi[liv] or about 0.29 μg of Am-241.

$$1 \times 10^{-6} \text{ Ci} / 3.428 \text{ Ci/g} = 0.29 \times 10^{-6} \text{ g } \mathbf{(0.29\ \mu g)}$$

Americium-241 is typically used in smoke detectors as a source of ionizing radiation. Inside of a smoke detector, the ionization chamber houses the Am-241. Alpha radiation given off by the Am-241 knocks off electrons from air molecules and creates charged particles. These charged particles move between the biased plates of the ionization chamber and create a very small but discernable current. When smoke enters the chamber, ionization is interfered with, causing a current drop and the alarm to sound.

Thus, to equal the strength of a 16 Ci oil well-logging device, a potential terrorist would need to amass around 16 million smoke detectors.

$$16 \text{ Ci} / 1 \times 10^{-6} \text{ Ci/smoke detector} = \textbf{16 million smoke detectors}$$

While smoke detectors are a real and available source of americium, they do not pose a significant threat because of the vast numbers required to make a source comparable strength to a logging device. Most homes in the United States contain at least one smoke detector and people are comfortable with them whether or not they are aware of the radiation. As a result a weapon made from smoke detectors would lack both the killing power of the radiation as well as the fear factor typically caused by the unknown.

**2. Cesium-137**

The scenario involves the release of Cs-137 obtained from a lost medical device. The FAS refers to a medical gauge that was discovered in North Carolina and exploded in Washington DC using 10 pounds of TNT. Immediate evacuation would not be necessary because the initial cloud of radioactivity would be relatively harmless. A five city block area centered at the blast would see cancer cases of one-in-a-thousand, while a forty block area would be contaminated beyond EPA standards, giving a resident a one-in-ten thousand chance of acquiring cancer. These areas must be abandoned if decontamination is not effective.[lv] The FAS scenario does not provide information on the strength of the lost North Carolina source. However, typical medical gauge sources range from 0.027-27 Ci,[lvi] but in this analysis the gauge has 0.011 Ci of Cs-137.[lvii] (407 MBq)

Cesium-137, as well as other isotopes, is regularly used for many different medical applications including treatment, diagnosis and research. The gamma energy from cesium-137 is typically used for cancer treatment or for instrument sterilization. Cobalt-60 is also used for cancer treatment and sterilization and is really the only other major medical isotope that would prove useful in a dirty bomb. Other common medical isotopes such as copper-67, iodine-123, iodine-131, technetium-99m, and xenon-133, used for various treatments, imaging, and studies, are not useful in dirty bombs because the half-lives are all less than 8 days. With such short half-lives, the isotopes are quickly rendered ineffective. Short half-lives also imply that specific activity is relatively high and that these materials are dangerous in amounts useful for a dirty bomb. The simple reality of a short half-life does not in itself mean that an isotope is ineffective in an RDD, it is just impractical to obtain, transport, build and position a weapon in such a short time.

Table 6. Cesium-137

| | |
|---|---|
| Specific Activity | 87.0 Ci/g |
| Half Life | 30.17 yrs |

The Cs-137 proposed in this scenario is a 0.011 Ci source with a mass of 12.6 mg.

This source would need to be shielded with about 2 cm of lead to reduce the 0.661 MeV gamma emissions by a factor of 10. Because of the amount of shielding involved with this type of gauge, simply walking away with the source would be cumbersome. However, the mass of the shielding alone may not deter a source such as this one from being targeted for potential use in a dirty bomb. The Goiana, Brazil case, mentioned earlier, illustrates that motivated people can move a source that has greater strength and is much heavier than this one.

In 1987 in Goiana, Brazil a large cesium device was scavenged from a former clinic and ultimately resulted in the release of Cs-137. This case is described in full detail earlier in this paper. Eventually, the cesium leak caused the death of four people and the screening of thousands more for potential contamination.

### 3. Cobalt-60

The scenario involves the use of a Co-60 rod obtained from a food irradiation facility and exploded in lower Manhattan by an unspecified amount of explosive. The rod has dimensions of 1” in diameter and 12” in length. Based on FAS assumptions the rod has been made into particulate form. FAS acknowledge that obtaining one of these sources is much less likely than the previous scenarios. Taking into account the specified dimensions and the density of cobalt, the rod has a mass of 1374.5 g.

$$\pi \times (1.27 \text{ cm})^2 \times 30.48 \text{ cm} \times 8.9 \text{ g/cm}^3 \text{ (density of cobalt)} = \mathbf{1374.5\ g}$$

Cobalt-60 is an ideal isotope for a dirty bomb attack because of the relatively short half-life and the resulting high specific activity. According to the FAS scenario, an area of over one thousand square kilometers would be contaminated, spreading into three states. For people living within three-hundred city blocks, the risk of death from cancer would be one-in-ten for some forty years. All of Manhattan Island would have a risk for cancer death of one-in-a-hundred and long-term contamination would result in vast amounts of useless space.

Table 7. Cobalt-60

| | |
|---|---|
| Specific Activity | 1130.36 Ci/g |
| Half Life | 5.272 yrs |

The 1374.5 g Co-60 source would thus have an activity of 1.55 MCi

This is considered a self-protecting source because of the high activity. To shield the 1.33 MeV gamma, 4 cm of lead would be needed to reduce the energy by a factor of 10, or 12 cm of lead to reduce the energy by a factor of 1000.[lviii] While security at food irradiation facilities takes into consideration the presence of cobalt-60, the source itself is so powerful that it would be very difficult for a terrorist to safely obtain. As it is, the legitimate movement of these sources requires much equipment, men and supervision.

As a self-protecting source, obtaining cobalt-60 from a food irradiation facility presents many problems. While the source itself is not too massive or bulky for an individual to carry alone, the source combined with enough shielding to make it safe would indeed be very cumbersome. It is entirely possible that a terrorist will not have regard for his own life and attempt to remove the source with insufficient shielding. Moving a source of this strength without sufficient shielding is not only likely fatal to the person moving it but to those near by as well. The source is also hot to the touch, further complicating unshielded movement. Assuming that a cobalt source could be removed from a food irradiation facility, it is not in the proper form to be dispersed as a weapon. The source is used in the form of a rod, thus would have to be further processed by the terrorist, which again involves a large amount of risk. In order to be useful the rod must be filed or ground into a powder to be dispersed and inhaled. This would again pose a handling and inhalation problem to the terrorist, enough so to be potentially deadly before a device is built or employed. Because of the self-protecting nature of cobalt-60 sources found at food irradiation facilities it is unlikely that a terrorist would successfully employ it. It is not impossible to obtain a self-protected source, however the casualties suffered during the process may not make it a valid option. Cobalt-60 is still a useful isotope for dirty bombs and should not be completely disregarded as a weapon. Smaller sources do exist, namely those used in hospitals for treatment and sterilization.

Food irradiation, while recently a controversial issue, is used world wide as an effective means of sterilizing food before it reaches the market place. Irradiation increases shelf life and also kills many types of harmful organisms. Typically, a cobalt-60 source is used to provide the gamma energy needed to irradiate food passed through the irradiation facility. Large sources are contained in steel tubes, stored underground in a water chamber when not in use. When needed, the sources are raised out of the ground and pallets of food items are passed through by a conveyer system. One benefit to using irradiation as a food processing method is that it does not cause a significant rise in the temperature of the food. Treatment at stable, room temperatures allows the food to retain most of its nutritional value and natural flavors. Another benefit of using strong sources of gamma energy is that the food can be irradiated in its final packaging material. None of the packaging material or food items become radioactive and the products are safe for shipping.[lix] The strength of cobalt-60 used in food irradiation facilities may seem to be a nice one-stop shop for dirty bomb material, but the strength of the source and its rod form render it self-protected.

### 4. Conclusions

Henry Kelly from the Federation of American Scientist paints a very grim and far reaching picture to the Senate Committee on Foreign Relations. He describes what might happen to a city that is affected by an attack using americium-241, cesium-137, or cobalt-60. While, clearly these attacks do pose a threat to the population, the likelihood of each attack varies. The most probable attacks are those using sources obtained from industry, such as americium-241 or sources obtained from a medical facility, such as cesium-137. The scenario involving cobalt-60 obtained from a food irradiation facility is the least likely due to the self-protecting nature of the source itself.

Dr. Kelly suggests that in order to minimize the threat of a dirty bomb, opportunities for possessing and availability of radioactive isotopes must be minimized first. In addition, early detection systems need to be in place and utilized, and the public must be educated as to real and imagined threats in order to keep casualties resulting from panic and chaos to a minimum.[lx] One of the biggest reasons isotopes become available to a terrorist is because when they are no longer useful, appropriate security or disposal do not exist. The high cost of properly handling materials in industrial facilities and at medical centers provides the greatest opening for terrorist. When an attack occurs first responders must have an effective way of determining that radiation actually is an issue. Following that, they need to know how to protect themselves and the rest of the general population. Knowledge in these areas will prevent the casualties of fear and chaos that quickly overload the response system.[lxi]

Objective analysis of the scenarios studied by the FAS show that indeed the isotopes considered do present a credible threat. Based on availability, cesium-137 is most likely to be used, followed by americium-241, and finally cobalt-60. From strictly an energetic point of view, cobalt and cesium are both desirable because they are gamma emitters and pose an external threat to contaminated individuals as well as an internal threat. Americium is an alpha emitter and thus is essentially harmless to an externally contaminated person because alpha particles do not penetrate skin. Internal americium contamination is a concern however because of the high amount of energy that alpha particles deposit locally. The long-term effects, centering on the risk of death from cancer, are overestimated however. Charles B. Meinhold, president emeritus of the National Council on Radiation Protection says, "studies of those survivors [of Hiroshima and Nagasaki bombings] since 1950 show that of 86,572 people exposed to levels of radiation thousands of time greater than a dirty bomb could produce, cancer deaths exceeded the expected numbers for that population by 335."[lxii] The numbers used by the FAS to describe the cancer risk are very high and do not represent an accurate picture of the risks associated with living in an area that has been attacked by a dirty bomb. The greatest long-term effect of such an attack may not be entirely calculable. Economic damage to a city would be high and far-reaching, as buildings may have to be demolished, disrupting trade and business. Another factor that could harm an areas economic potential is the stigma that arises because of radioactive contamination, whether or not the area is fully decontaminated.

Overall, these scenarios illustrate how fear, chaos, and economic loss will pose the greatest challenges to a city and its first responder struck by a dirty bomb. Initial casualties in such an attack will be isolated to those caused by blast effects, with a very small chance of any acute radiation dose deaths. Even long-term deaths associated with exposure from a typical dirty bomb are likely to be small and possibly undistinguishable from other background causes of cancer. The material needed to create panic is available, however knowledge of the realities and real threats involved with a dirty bomb attack will spare much undue loss.

## C. TOP OFFICIAL EXERCISE SERIES – TOPOFF 2

The Department of Homeland Security designed and executed the most comprehensive terrorism response exercise, involving the highest levels of government, ever carried out in the United States. TOPOFF 2, named for the second exercise involving top government officials, was conducted from May 12 to May 16, 2003. The exercise involved federal, state, local (FSL), and Canadian authorities responding to a terrorist attack by RDD in Seattle, Washington and a pneumonic plague in Chicago. In responding to these incidents, the goals were to identify weaknesses in the response system, improve management of extreme events, form more effective interlocking management systems, validate authorities, strategies, plans, policies, procedures and protocols, and finally to improve the national training program for extreme events.[lxiii] Incorporated into the design of TOPOFF 2 was an introduction to specific scenarios. This allowed the actors to be increasingly aware of the situation and fostered a more complicated exercise.

In reviewing the exercise and determining how to further meet these stated goals, the focus was more on the decision and coordination process rather than particularities of the actual events. This type of analysis is likely to be of interest to first responders because it provides insight into practical issues that should be considered during an RDD attack. While the previously described scenario involving a FAS analysis dealt with a specific type of attack, and the nature and consequences of the attack, a TOPOFF 2 analysis should provide insight in a broader sense. Two critical decisions that this exercise allowed involved raising the homeland security threat condition to Red by various levels of FSL authorities and requesting Presidential declarations to address RDD and bioterrorism attacks. Most relevant to an RDD attack were the issues of data collection and coordination and the safety of the first responders verses that of rescuing casualties.

### 1. Data Collection

Collecting data is the job of many FSL agencies and requires compilation processing at many different locations. The refined data is then given to top officials help guide their decision making process. Data collection and coordination is especially crucial in an RDD attack, but the Seattle scenario revealed some complications in this process that affected the overall response. Coordination between all FSL authorities proved insufficient both at the site of the incident and at off site centers. It became clear that many assets for collection are available, but coordination of those assets is more important. Working with the Federal Radiological Monitoring and Assessment Center is necessary for overall coordination. Not only is data collection critical in the case of an RDD attack, so is additional education among first responders and decision makers. Know what information is relevant at what time as well as the value of different models such as the one used in the FAS analysis. Models may be useful to some extent, however as actual data is collected a real picture is created and the value of a model decreases. This paper seeks to provide some of the necessary education as well as identify areas that need further consideration.

### 2. First Responder Safety

The issue of safety of the first responder verses the rescue of victims is also addressed by the TOPOFF 2 exercise. When dealing with an RDD attack, responders have a greater chance of becoming a casualty because they can be contaminated by the effects of the device or by a contaminated victim. The exercise allowed for an initial awareness of the type of attack and the fact that it involved radiation. This knowledge allowed responders to proceed with the rescue operation while incident commanders evaluated the safety of the responders themselves. This aspect of the exercise is a bit artificial because in an attack such as this, there is no initial indication that radiation exists. In reality, blast effects from an RDD are immediately more life threatening than radiation effects and should be responded to as such. Still it is prudent for the first responder to be familiar with radiation and contamination. More communication between the incident commander and hospital control is needed. Hospital control needs to provide to incident command a more comprehensive risk-benefit analysis in order to facilitate faster on scene response. Keeping responders safe as well as rescuing victims requires public health, medical communities, media, and the general public to be educated about the facts of an RDD. Education limits public concern and media sensationalism, while allowing responders to continue with their work effectively and safely. A consistent message to the general public from incident command is essential in balancing the safety of first responders with the rescue of victims.

### 3. Conclusions

As the largest exercise ever conducted by the United States dealing with weapons of mass destruction, TOPOFF 2 was important in providing not only top officials with decision making practice, but first responders with some issues to consider. The most important aspect of TOPOFF 2 for this paper was the scenario played out in Seattle, Washington involving the use of an RDD. By incorporating many different FSL authorities, issues involving communication and coordination were revealed. Data collection and processing for the RDD attack need to be improved so that a more effective and timely response can occur. The safety of responders verses rescuing victims is another important issues during and RDD attack. Radiation is not detectable by human senses, potentially resulting in a false sense of security for the responder. Clearly blast effects from an RDD will be the most acute concern while responding. However, more communication between hospital central and incident commanders in regards to radiation will provide greater overall safety. TOPOFF 2 is an important exercise for providing first responders with issues worth considering before responding to an RDD attack.

## D. OPERATION CRITICAL RESPONSE – LOS ANGLES COUNTY

Each year the county of Los Angeles is required by California State law and by Los Angeles County Code to carry out one operational countywide emergency exercise. In November of 2002 an exercise called "Operation Critical Response" was conducted involving the use of multiple RDDs. In California, response to such incidents is organized under the Standardized Emergency Management System (SEMS) in an effort to enhance information flow and coordination. By organizing under one system, coordination and information is available at the site of the incident, locally, in an operationally area, regionally, or at the state level. The 2002 exercise involved explosions in Pasadena, Long Beach, Carson, Burbank, Torrance, and Santa Fe Springs all within the hour of 0900-1000. Half of the explosions were dirty bombs, while two others had chemicals and the final explosion was a mass casualty incident. Many spontaneous and simultaneous evacuations occurred due to fear and the resulting panic for radiation. This scenario caused all major freeways to backup, resulting in the delay of aid units and overloaded hospitals with people who thought they had been exposed to radiation. Air traffic is halted as most airports are closed, the homeland security threat condition is raised to red, and some public employees do not go to work because they feel targeted. An NBC news affiliate was able to put out a 20-minute news video used to start to the exercise.

The exercise, like TOPOFF 2, was used by Los Angeles County to discover issues and concerns dealing with communication and other logistics specific to an RDD attack. One thing, specifically relevant to first responders regarding dirty bombs, included the definition of the weapon as an area denial weapon as opposed to a mass casualty weapon. This was important because it effected overall coordination of the immediate response as well as the continuing response and asset allocation. Severe injuries will not likely be the result of radiation, so it is more important to stabilize and close off an area first and test for radiation later. Another issue was the large flux of people at the hospitals, especially in sorting out "worried well" from those that are truly contaminated. Blast effects being the most likely acute cause of death from a dirty bomb brings up the issue of how the coroner deals with contaminated or even potentially contaminated persons. Other concerns brought out by the exercise include preventing further contamination by vehicles and individuals as well as maintaining the continuity of government. These issues were determined by the local agencies to be the most important to address, areas of weakness during an RDD attack.

Some potential solutions to the issues of concern arose from the exercise however. In the case of overcrowded hospitals filled with worried well patients, local fire and police departments established a screening area in front of hospitals to alleviate unnecessary emergency room traffic. Potentially, one of the most troublesome aspects of an RDD attack is actually identifying the fact that radiation is involved. There are no physical indications and no way to detect radiation with human senses. In this scenario, threats of attacks incorporating radiation were known, thus first responders approached each scene with that assumption. In addition to the threat of radiation, once its presence was confirmed at one site, other responders acted accordingly to locate radiation at all sites. Identifying the presence of radiation is not always easy and perhaps the best solution comes from intelligence and assuming its presence. Another activity that was heavily relied upon in this scenario was on-site visual reports of information rather than plume modeling or any other predictive method. Modeling can be useful for generating a likely sequence of events, however there are too many factors that need to be addressed, thus on-site information is most useful during a response.

#### 1. Conclusions

Los Angeles County's Operation Critical Response was an important exercise not only for the agencies in and around Los Angeles County, but also for the first responder community as a whole. By conducting an exercise that incorporated multiple RDD events as well as other explosives and chemicals, many important issues and areas of consideration arose. Large-scale events such as those contained in this scenario always demand a high level of coordination and communication. The exercise raised specific concerns involving flooded hospitals, blocked freeways, and securing areas without causing undue panic. Modeling again proves useful only in the general sense, while on-site data is most important during an event. As was the case with the TOPOFF 2 exercise, Operation Critical Response was a large-scale event that sought to prepare first responders for actual scenarios. What can be learned from the exercises are the areas most likely to be relevant during an RDD event. Overall awareness provides focus for training and consideration prior to a real-life event.

# VI. CONCLUSION

In recent years the term “dirty bomb” has surfaced, thrown out by media circles, politicians, scientist, and the general population. Often times people refer to the potential terrorist act of setting off a dirty bomb, causing destruction and uncertainty. Most of the fear associated with a dirty bomb however is actually tied to the public perception that anything dealing with nuclear or radiological devices is dangerous. The general population may have an understanding of what a dirty bomb is but typically do not really understand its physics or effects. Most people are unaware of the real dangers or lack thereof associated with a dirty bomb. Radiation itself is colorless, odorless, tasteless and otherwise undetectable by human senses without the use of instruments. This aspect alone is probably the greatest weapon in the hands of a terrorist. Unlike a nuclear bomb which produces its power from energy stored in the center of uranium or plutonium atoms, a dirty bomb simply uses a conventional explosive such as TNT or another modern or plastized explosive, packed with any one or a mixture of the thousands of radioactive isotopes in existence. Fortunately, only a select number of radioactive isotopes are useful for dirty bombs because of their availability, relative strength, or half-life. The vast majority of isotopes are not useful to a terrorist because the half-life is too short to be practical, or too long to have significant activity. Some isotopes are self-protected and would likely kill any terrorist that attempted to move them without appropriate training and shielding. Other isotopes are subjected to high security or are available in very small impractical quantities. As a result, only a handful of isotopes truly pose an RDD threat.

The immediate killing power of a dirty bomb is due strictly to the blast affects of the conventional explosive. However in addition to destroying whatever is in close proximity, a dirty bomb also spreads the radioactive isotopes into the environment. The real effects of isotopes included in such a weapon are to create uncertainty and chaos. Economic damage resulting from a dirty bomb will likely be significant. Contaminated areas most likely will carry a negative connotation with their name, as has been the case, as a result business, trade, and residents will be lost. The resulting contamination from a dirty bomb should in no way hinder the first responder’s efforts to provide aid to casualties however. Improperly trained first responders can perpetuate the fear associated with such a weapon if they themselves drastically change the way they respond. For these reasons dirty bombs, or RDDs can be called weapons of mass disruption rather than strictly weapons of mass destruction.

Strictly speaking, just about anyone can build a dirty bomb because it involves nothing more than building a conventional bomb, the results of which are seen weekly in world media. The difficult aspect in making a dirty bomb, however, is in obtaining and transporting the radiological material. As a rule radioactive isotopes are considered dangerous and most governments have programs that monitor all radioactive material under their jurisdiction. The problem lays in the areas of the world where control is less stringent or when radioactive materials escape from the system of control. Most often this occurs in former Soviet countries or in Eastern Europe where regulation has broken down or simply does not exist. Sources of radioactive material may not be as exclusive as the general population is led to believe. The use of radioactive isotopes stretches into many aspects of life, from the obvious nuclear power plants, university and research laboratories to industrial gauges, medical screening and treatment equipment, and food irradiation facilities, to even the household smoke detector. In the strictest sense of the word, a dirty bomb has not yet been used in a terrorist attack, however there are a number of cases in which terrorists with malicious intent have struck using radioactive isotopes. There are also cases in which accidents or neglect has caused the dispersal of radioactive material. The potential exists for such an attack, however the key to responding to a dirty bomb is knowledge and education. An educated first responder community understands the particularities of a radiological dispersion event and can respond in such a way as to save lives and minimize panic. With a little knowledge an educated public can respond rationally to issues of radiation and conduct business following an attack.

# APPENDIX: PHYSICAL CONSTANTS AND NOTES ON IMPORTANT ISOTOPES

The following tables are provided as a source of information on isotopes that are most likely to be used in the event of an RDD or dirty bomb. The choice on these isotopes is based on availability, historical use, and practicality in terms of half-life and specific activity. Physical and chemical properties[lxiv, lxv] are included and remain constant for all isotopes of an element, while radiophysical properties[lxvi] are specific to each individual isotope.

| **Americium** | | |
|---|---|---|
| Atomic Number: | 95 | |
| Physical Properties: | In the metallic form it is silvery-white in color and tarnishes slowly in air. | |
| Chemical Properties: | Produced by a reduction of americium trifluoride by barium vapor. | |
| Hazards: | All isotopes of americium are radioactive. | |
| Important Isotopes: | **Americium-241** | |
| | Use | Smoke detectors, well-logging |
| | Half Life | 432 years |
| | Gamma Energies | 0.0595, 0.0263 MeV |
| | Other Energies | 5.4857, 5.4430 $\alpha$ |
| | Production | Pu-241 daughter |
| | Specific Activity | 3.428 Ci/g |

| **Cadmium** | | |
|---|---|---|
| Atomic Number: | 48 | |
| Physical Properties: | Bluish-white in color, soft, ductile, and malleable metal | |
| Chemical Properties: | Produced as an impurity precipitated during the processing of zinc ore. | |
| Hazards: | Toxic when inhaled, accumulates in the body | |
| Important Isotopes: | **Cadmium-113** | |
| | Use | Industrial, reactor fuel product |
| | Half Life | 13.7 years |
| | Gamma Energies | none |
| | Other Energies | 0.59 MeV β- |
| | Production | Cd-112(n,γ), fission |
| | Specific Activity | 231 Ci/g |

| **Californium** | | |
|---|---|---|
| Atomic Number: | 98 | |
| Physical Properties: | Synthetic metal | |
| Chemical Properties: | All isotopes of californium are radioactive | |
| Hazards: | Radioactive | |
| Important Isotopes: | **Californium-252** | |
| | Use | Reactor, reactor fuel products |
| | Half Life | 2.64 years |
| | Gamma Energies | 0.0434, 0.100 MeV |
| | Other Energies | 6.118, 6.076 $\alpha$ |
| | Production | multiple n capture from U-238, Pu-239, Cm-244 |
| | Specific Activity | 536.3 Ci/g |

| | | |
|---|---|---|
| **Cesium** | | |
| Atomic Number: | 55 | |
| Physical Properties: | Silver-white, soft, ductile, metal. | |
| Chemical Properties: | Decomposes in water producing free hydrogen gas and subsequent ignition. Must be kept under kerosene. | |
| Hazards: | Fire hazard | |
| Important Isotopes: | **Cesium-137** | |
| | Use | Medical and industrial use, often found as cesium chloride salt. |
| | Half Life | 30.17 years |
| | Gamma Energies | 0.66165 MeV |
| | Other Energies | 0.512 MeV $\beta^-$ |
| | Production | fission product |
| | Specific Activity | 87.0 Ci/g |

| | | |
|---|---|---|
| **Cobalt** | | |
| Atomic Number: | 27 | |
| Physical Properties: | Steel gray, slightly pinkish, shiny, hard, ductile,<br>Slightly malleable, magnetic metal | |
| Chemical Properties: | Slightly soluble in dilute hydrochloric and sulfuric acid, and readily soluble in nitric acid. | |
| Hazards: | No important hazards | |
| Important Isotopes: | **Cobalt-60** | |
| | Use | Industrial testing and food irradiation |
| | Half Life | 2.0 barns |
| | Gamma Energies | 1.3325, 1.1732 MeV |
| | Other Energies | 0.3179 MeV $\beta^-$ |
| | Production | Co-59(n,$\gamma$) |
| | Specific Activity | 1130.36 Ci/g |

| | | |
|---|---|---|
| **Hafnium** | | |
| Atomic Number: | 72 | |
| Physical Properties: | Silver-gray, ductile, lustrous metal. | |
| Chemical Properties: | Very corrosion resistant | |
| Hazards: | Not toxic, fine powders can combust | |
| Important Isotopes: | **Hafnium-181** | |
| | Use | Industrial by-product |
| | Half Life | 42.4 days |
| | Gamma Energies | 0.4820, 0.1330 MeV |
| | Other Energies | 0.408 MeV $\beta^-$ |
| | Production | Hf-180(n,$\gamma$) |
| | Specific Activity | $1.7018 \times 10^4$ Ci/g |

| | | |
|---|---|---|
| **Iridium** | | |
| Atomic Number: | 72 | |
| Physical Properties: | Silvery-white in color, hard, and brittle metal. | |
| Chemical Properties: | Most corrosion resistant element known. | |
| Hazards: | Uncreative, not toxic | |
| Important Isotopes: | **Iridium-192** | |
| | Use | Industrial testing |
| | Half Life | 73.83 days |
| | Gamma Energies | 0.31651, 0.46807 MeV |
| | Other Energies | 0.666, 0.535 MeV $\beta^-$ |
| | Notes | Also undergoes electron capture |
| | Production | Ir-191(n,$\gamma$) |
| | Specific Activity | 7.7 Ci/g |

| **Strontium** | | |
|---|---|---|
| Atomic Number: | 38 | |
| Physical Properties: | Pale yellow, soft metal | |
| Chemical Properties: | Decomposes in water producing free hydrogen gas and subsequent ignition. Must be kept under kerosene or naphtha oil. | |
| Hazards: | Fire hazard | |
| Important Isotopes: | **Strontium-90** | |
| | Use | Industrial use and radiothermal batteries |
| | Half Life | 29.0 years |
| | Gamma Energies | none |
| | Other Energies | 0.546 MeV $\beta^-$ |
| | Production | fission product |
| | Specific Activity | 139.4Ci/g |

| | | |
|---|---|---|
| **Tantalum** | | |
| Atomic Number: | 73 | |
| Physical Properties: | Steel gray-blue color when unpolished and platinum white when polished | |
| Chemical Properties: | Insoluble in acids, extremely corrosion resistant | |
| Hazards: | No important hazards | |
| Important Isotopes: | **Tantalum-182** | |
| | Use | Industrial by-product |
| | Half Life | 114.5 days |
| | Gamma Energies | 0.06775, 1.1213, 1.22141 MeV |
| | Other Energies | 0.522, 0.246 MeV $\beta^-$ |
| | Production | Ta-181(n,$\gamma$) |
| | Specific Activity | 6239 Ci/g |

| **Thulium** | | |
|---|---|---|
| Atomic Number: | 69 | |
| Physical Properties: | Metallic, shiny, lustrous metal | |
| Chemical Properties: | Reacts slowly with water and is soluble in dilute acid, forms green colored salts. | |
| Hazards: | Stable in air. | |
| Important Isotopes: | **Thulium-170** | |
| | Use | Industrial testing as a portable x-ray source |
| | Half Life | 129 days |
| | Gamma Energies | 0.084252 MeV |
| | Other Energies | 0.968, 0.883 MeV $\beta^-$ |
| | Notes | Also undergoes electron capture |
| | Production | Tm-169(n,$\gamma$); Er-170(p,n) |
| | Specific Activity | 5973 Ci/g |

| | | |
|---|---|---|
| **Ytterbium** | | |
| Atomic Number: | 70 | |
| Physical Properties: | Silvery-white metallic solid, though soft and ductile. | |
| Chemical Properties: | Quickly reacts and dissolves in acids, reacts slowly in water. | |
| Hazards: | Not toxic | |
| Important Isotopes: | **Ytterbium-169** | |
| | Use | Industrial testing |
| | Half Life | 32.02 days |
| | Gamma Energies | 0.063121, 0.19796, 0.17721, 0.10978 MeV |
| | Other Energies | none |
| | Notes | Undergoes electron capture |
| | Production | Yb-168(n,$\gamma$); Tm-169(d,2n); Lu-169 daughter; protons on Ta |
| | Specific Activity | $2.4128 \times 10^4$ Ci/g |

| | | |
|---|---|---|
| **Zirconium** | | |
| Atomic Number: | 40 | |
| Physical Properties: | Grayish-white, lustrous metal | |
| Chemical Properties: | Very corrosion resistant | |
| Hazards: | Not toxic, divided dust can combust | |
| Important Isotopes: | **Zirconium-93** | |
| | Use | Industrial by-product |
| | Half Life | $1.5x10^6$ years |
| | Gamma Energies | 0.0304 MeV |
| | Other Energies | 0.060 MeV $\beta^-$ |
| | Production | fission product |
| | Specific Activity | 0.00251 Ci/g |

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